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Multipacket reception in the presence of in-band full-duplex communication

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To my parents, grandparents
and girlfriend

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"I will either find a way or make one"

General Hannibal Barca

Abstract

In-Band Full-DupleX (IB-FDX) is defined as the ability for nodes to transmit and receive signals simultaneously on the same channel. Conventional digital wireless networks do not implement it, since a node's own transmission signal causes interference to the signal it is trying to receive. However, recent studies attempt to overcome this obstacle, since it can potentially double the spectral efficiency of current wireless networks. Different mechanisms exist today that are able to reduce a significant part of the Self-Interference (SI), although specially tuned Medium Access Control (MAC) protocols are required to optimize its use. One of IB-FDX's biggest problems is that the nodes' interference range is extended, meaning the unusable space for other transmissions and receptions is broader. This dissertation proposes using MultiPacket Reception (MPR) to address this issue and adapts an already existing Single-Carrier with Frequency-Domain Equalization (SC-FDE) receiver to IB-FDX. The performance analysis suggests that MPR and IB-FDX have a strong synergy and are able to achieve higher data rates, when used together. Using analytical models, the optimal transmission patterns and transmission power were identified, which maximize the channel capacity with the minimal energy consumption. This was used to define a new MAC protocol, named Full-duplex Multipacket reception Medium Access Control (FM-MAC). FM-MAC was designed for a single-hop cellular infrastructure, where the Access Point (AP) and the terminals implement both IB-FDX and MPR. It divides the coverage range of the AP into a closer Full-DupleX (FDX) zone and a farther Half-DupleX (HDX) zone and adds a tunable fairness mechanism to avoid terminal starvation. Simulation results show that this protocol provides efficient support for both HDX and FDX terminals, maximizing its capacity when more FDX terminals are used.

Keywords: Digital wireless networks; In-band full-duplex; Multipacket reception; Inter-terminal interference.

Resumo

Comunicação full-duplex na mesma banda (IB-FDX) traduz-se na capacidade dos nós transmitirem e receberem sinais simultaneamente no mesmo canal. Redes sem fios digitais convencionais não implementam esta tecnologia pois o sinal que é transmitido por um nó causa interferência no sinal que este quer receber. No entanto, estudos recentes procuram superar este obstáculo, já que tem o potencial de duplicar a eficiência espectral das redes sem fios atuais. Existem várias abordagens para reduzir o *ruído interferente próprio* (SI), mas requerem protocolos de *controlo do acesso ao meio* (MAC) especiais para optimizar a sua utilização. Um dos maiores problemas do IB-FDX é que o alcance da interferência dos nós é estendido, o que resulta numa área inutilizável para outras transmissões e recepções mais abrangente. Esta dissertação propõe utilizar *recepção multi pacote* (MPR) para superar este obstáculo e adapta um receptor com *equalização no domínio da frequência de portadora única* (SC-FDE) a IB-FDX. Os resultados sugerem que MPR e IB-FDX possuem uma sinergia forte que os permite alcançar ritmos superiores quando usados em conjunto. Através de modelos analíticos, foram identificados padrões e potências de transmissão ideais, que permitem maximizar a capacidade do canal com o consumo de energia mínimo. Estas referências foram utilizadas para definir um novo protocolo MAC chamado *controlo do acesso ao meio com recepção multi pacote e full-duplex* (FM-MAC). O protocolo foi desenhado para uma rede celular infraestruturada onde o *ponto de acesso* (AP) e os terminais utilizam IB-FDX e MPR. O protocolo divide o alcance de cobertura do AP numa zona *full-duplex* (FDX) e numa zona *half-duplex* (HDX) e apresenta um mecanismo de justiça configurável que impede que os terminais fiquem sem acesso ao canal. Os resultados mostram que este protocolo suporta terminais HDX e FDX eficientemente, maximizando a sua capacidade quando são utilizados mais terminais FDX.

Palavras-chave: Redes sem fios digitais; Comunicação full-duplex na mesma banda; Recepção multi pacote; Interferência inter-terminal.

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Acronyms

ACK ACKnowledgement control packet

ADC Analog-to-Digital Converter

AP Access Point

APTX Access Point Transmission

At-BB At-BaseBand

At-RF At-Radio-Frequency

B-NDMA Blind Network-assisted Diversity Multiple Access

BER Bit-Error Rate

BS Base Station

CA Collision Avoidance

CD Collision Detection

CDMA Code Division Multiple Access

CRC Cyclic Redundancy Check

CSI Channel State Information

CSMA Carrier Sense Multiple Access

CTS Clear-To-Send

DAC Digital-to-Analog Converter

DO Downlink Only

DP Drop Packet

EPUP Energy Per Useful Packet

FD-MAC Full-Duplex Medium Access Control

FDMA Frequency Division Multiple Access

FD Full-Duplex

FDX Full-DupleX

FF-NDMA Feedback-Free Network-assisted Diversity Multiple Access

FFT Fast Fourier Transform

FIFO First In First Out

FM-MAC Full-duplex Multipacket reception Medium Access Control

H-ARQ Hybrid Automatic Repeat reQuest

H-NDMA Hybrid automatic repeat request Network Division Multiple Access

HD Half-Duplex

HDX Half-DupleX

HPA High-Power Amplifier

HOL Head-Of-Line

IB-DFE Iterative Block Decision-Feedback Equalizer

IB-FDX In-Band Full-DupleX

ICA-CooPNDMA Independent Component Analysis CooPerative Network-assisted Diversity Multiple Access

ICA-NDMA Independent Component Analysis Network-assisted Diversity Multiple Access

ID IDentification

IEEE Institute of Electrical and Electronics Engineers

IFFT Inverse Fast Fourier Transform

ITI Inter-Terminal Interference

ITU International Telecommunication Union

JFI Jain's Fairness Index

LAN Local Area Network

LNA Low-Noise Amplifier

LR-WPN Low-Rate Wireless Personal area Network

LTE Long-Term Evolution

MAC Medium Access Control

MAI Multiple Access Interference

MIDU MImo full-DUplex

MIMO Multiple-Input and Multiple-Output

MPR MultiPacket Reception

MPR-IC MultiPacket Reception by successive Interference Cancellation

MPR-T MultiPacket Reception by Time diversity

MSE Mean Square Error

MT Mobile Terminal

MUD MultiUser Detection

NA Not Applicable

NDMA Network-assisted Diversity Multiple Access

OFDMA Orthogonal Frequency Division Multiple Access

OQPSK Offset Quadrature Phase-Shift Keying

PER Packet Error Rate

PHY PHYsical layer

PIC Parallel Interference Cancellation

PR Packets Received

QPSK Quadrature Phase Shift Keying

RF Radio-Frequency

RTS Request To Send

RTXN ReTransmission Needed

S-FDX Semi Full-DupleX

SC-FDE Single-Carrier with Frequency-Domain Equalization

SI Self-Interference

SIC Self-Interference Cancellation

SICTA Successive Interference Cancellation Tree Algorithm

SINR Signal-to-Interference-plus-Noise Ratio

SIR Self-Interference Reduction

SPR Single Packet Reception

SPR-T Single Packet Reception by Time diversity

SRB Shared Random Backoff

SYNC SYNCronization control packet

TUOS Terminal Unique Orthogonal spreading-Sequence

UND Uplink aNd Downlink

UO Uplink Only

WAN Wireless Access Networks

WLAN Wireless Local Area Network

1 Introduction

Ever since modern wireless digital communication was first used in the Hawaiian Islands in the early 1970s that it has been an evolving subject. At the time the researchers were looking for a way to connect the computers at the University of Hawaii to the main computer in Honolulu. This way the ALOHANET system was born and offered a simple way to transmit packet data wirelessly [Tan10]. Thanks to the constant development and research in the area of wireless networks, this segment of the communications industry has grown from simple system, to one of the most important and fast moving industries around [Gol05; Mol10].
Current Wireless Access Networks (WAN) consume at least 10 times more power than wired technologies when providing comparable access rates and traffic volumes [BAHT11]. Also, they present a higher and time-varying error rate which makes them less reliable in certain scenarios. However, the portable nature of their design allows for easier installation and better mobility than the wired alternative, making WANs extremely versatile, flexible and practical. Conventional WANs operate in Half-DupleX (HDX) or out-of-band Full-DupleX (FDX), meaning that MTs transmit and receive either at different times, or by enabling multiple signals to occupy channels that are separated into orthogonal signalling dimensions [SSGBRW14; LSW12]. Recent studies have shown a significant interest in re-architecting terrestrial communications systems, such as Institute of Electrical and Electronics Engineers (IEEE) 802.11 and cellular systems, to leverage In-Band Full-DupleX (IB-FDX) (ability for a terminal to receive and transmit in the same frequency band simultaneously) [SSGBRW14]. IB-FDX is not a new concept, as radar systems have been using it at least since the 1940s. However, most terrestrial wireless communication

systems like cellular and IEEE 802.11 avoid IB-FDX, since the idea of transmitting and receiving signals on the same channel has always been considered ineffective due to the interference generated [SSGBRW14; Gol05]. Most studies agree that if the interference generated by the node can be suppressed successfully, transmitting and receiving using the same dedicated bandwidth can double the spectral efficiency of a system which in turn can double the throughput in comparison to an ordinary HDX system [BMK13; NTPL14; DMBS12a; CJSLK10]. [CJSLK10] considers that despite this being IB-FDX's main advantage, the systems can still benefit from much more than higher data rates at the physical layer.

[CJSLK10] presents a design where it is suggested that the Access Point (AP) should always be forwarding packets to a destination while it is receiving packets from a source. This allows the other nodes in the network to recognize that a transmission is already in progress forcing them to delay their transmissions and thereby avoiding collisions (solving the hidden node problem). In [CTK14] it is shown how the interference generated from all nodes using the dedicated bandwidth simultaneously can be optimized to act as artificial noise against passive attackers (radio eavesdroppers). This allows an improvement of the secrecy of the messages transmitted at the physical level. [CJSLK10] also shows a FDX radio that (unlike traditional HDX radios) is capable of sensing while transmitting in order to avoid collisions. This is particularly useful when considering cognitive radio applications, as secondary users can only use the dedicated bandwidth if the primary user is not using it at that moment. IB-FDX communication was also used to enable relay switching, creating a one-way flow of data traffic [MB12].

Despite the real-world applications and benefits of IB-FDX, two main obstacles lie in the way of enabling this technology. One is the interference that a transmitting IB-FDX terminal causes to itself, which interferes with the desired signal being received by that terminal. The second is Inter-Terminal Interference (ITI), which occurs in IB-FDX networks between terminals that may themselves be non-IB-FDX [SSGBRW14].

The work developed in this dissertation intends to address the ITI by applying Multi-Packet Reception (MPR) techniques. MPR is a technology that allows a node to receive more than one packet from multiple concurrent transmissions, making it possible to decode the packets, even if a collision occurred [LSW12].

1.1 Research goals and contributions

This research work has two main goals:

- The implementation of a system that uses MPR to handle the ITI generated by IB-FDX communications;
- The design of a Medium Access Control (MAC) protocol that optimizes channel access.

Both goals were achieved during the dissertation, which contributed with:

- A physical layer analysis of the performance of the MPR IB-FDX system. The model presented in chapter 3 was accepted for publication in the *2015 ICC's Workshop 5G & Beyond - Enabling Technologies and Applications* [BBDOPA15];
- A MAC protocol named Full-duplex Multipacket reception Medium Access Control (FM-MAC) was designed and a system level simulator was implemented using MATLAB, which considers the physical layer performance models. We plan to prepare a conference paper covering the FM-MAC protocol, and an extended version, with a stochastic system level's performance model, for a journal.

1.2 Dissertation's outline

This rest of this dissertation is organized as follows:
Chapter 2 starts by classifying the different types of mechanisms proposed to enable IB-FDX communication as well as some of the most noteworthy designs. A small description of the current state of the art of MPR technology is given, as a possible solution to address the interference sensitivity of IB-FDX networks, therefore proving the relevance of the system developed in this dissertation.
Chapter 3 starts by analytically describing the MPR receiver from [GDBO12] and by the modifications that were performed in order to have it support IB-FDX communication. This is followed by an analysis of how the interference generated by the transmission of a FDX transceiver influences the performance of MPR systems. It then presents a set of simulations that characterize a system in which nodes support IB-FDX and MPR.
Chapter 4 describes the FM-MAC protocol that is able to control a single-hop cellular infrastructure system, where the AP supports both IB-FDX and MPR. The performance is evaluated using a set of simulations that measures the effects the relation between the number of HDX and FDX MTs have in the system's delay, throughput and Energy Per Useful Packet (EPUP).
Chapter 5 summarizes the conclusions of the work and presents suggestions for future work that can be done in order to improve the system and MAC protocol described in this dissertation.

2

Related Work

2.1 Introduction

Over the years there has been some major breakthroughs in the area of digital wireless communications, with the focus on achieving a higher data transfer rate and bandwidth efficiency. Future developments will continue this trend, requiring protocols that are efficient at the physical layer and optimized at the uppers layers, to attain a higher spectral efficiency than the ones we already possess with the techniques that are available at the current time [Bha06].

Telecommunications standards have proposed two approaches for two-way communication: HDX and FDX transmission. HDX transmission is a two-way non-simultaneous communication, whereas FDX transmission is a two-way simultaneous communication. In other words, in a HDX scenario the nodes take turns transmitting while in a FDX scenario nodes can transmit and receive at the same time.

Current systems usually use separate uplink and downlink channels as a way to achieve FDX communication. These channels are separated using orthogonal signalling dimensions, such as time or frequency (e.g. IEEE 802.11 or Long-Term Evolution (LTE)) [Gol05]. This leads to a loss of spectral efficiency as the same channel can only be used for one transmission [BMK13]. Recent research focused on developing IB-FDX radios. This is a major paradigm shift in wireless communications, as the idea of transmitting and receiving signals on the same channel has always been considered ineffective due to the Self-Interference (SI) generated [Gol05]. This concept has the potential to double the spectral efficiency.

In IB-FDX systems, SI has to be dealt with in order for the signal to be received properly. Recent studies [DS10; ESS13; SPDS13; DMBS12b; CJSLK10; AKSRC12; KLA13; BMK13;

JCKBSSLKS11] proposed different techniques to cancel this SI.
The prototypes developed often involve additional hardware to implement the IB-FDX transmission, usually using different antennas for transmission and reception, although more ambitious designs use a single antenna for both [Kno12; BMK13]. It was also shown that although IB-FDX increases the bandwidth efficiency, it also increases the interference sensitivity [XZ14], reducing its effectiveness in a multi-hop network.
This chapter starts by classifying the different types of mechanisms proposed to reduce the levels of SI, providing a small description for each one and giving examples of designs that use those mechanisms. Secondly, some of the most noteworthy FDX architectures are described, compared and contrasted. Afterwards, some of the most meaningful MAC protocols developed for IB-FDX are explained. Lastly, a small description of the current state of the art of MPR technology is given, as a possible solution to address the interference sensitivity of IB-FDX networks to transmissions of external nodes.

2.2 Self-interference reducing methods

As mentioned before, the biggest problem that the scientific community is having with the development of IB-FDX radios is the amount of SI generated at a FDX node. This results from the fact that the transmit and receive antenna are either the same or relatively close to each other. These conditions make the SI at the receiver antenna much stronger than the signal that it actually wants to receive.

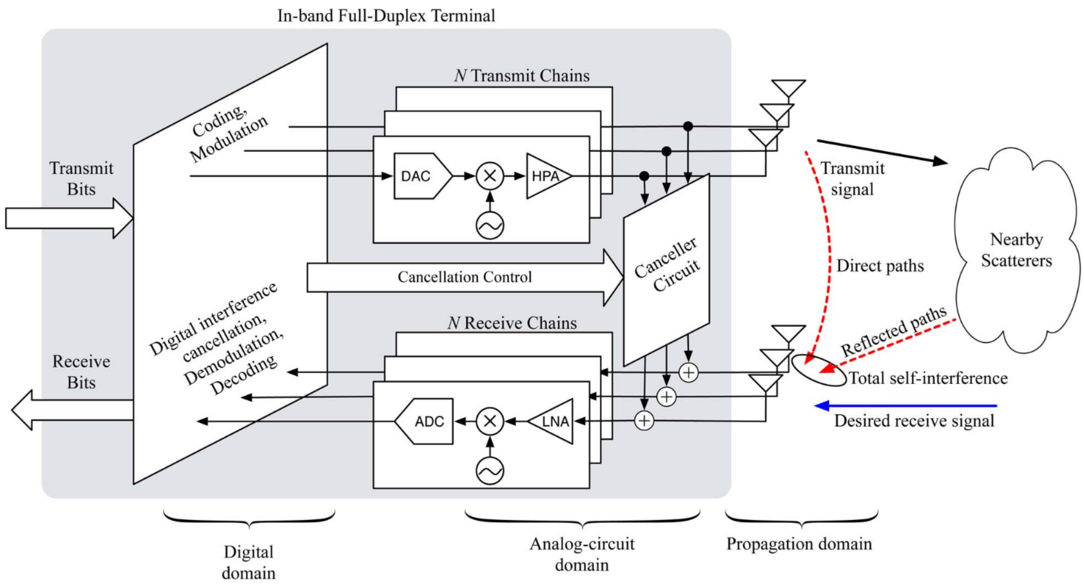


Figure 2.1: Anatomy of a separate-antenna IB-FDX node with multiple transmit antennas and multiple receive antennas. Adapted from [SSGBRW14].

SI reducing methods can be classified as either passive or active. Passive suppression techniques focus on magnetically isolating the transmit from the receive antenna. Active suppression methods, on the other hand, use the knowledge of its own transmit signal to cancel the SI, by injecting a cancellation waveform into the receive signal path to null the SI [ESS13]. This cancellation waveform is an inverted copy of the original signal. Figure 2.1 depicts a conventional separate-antenna IB-FDX node. The transmission chain of the transceiver accepts a bitstream that is coded and modulated in the digital domain. This bitstream is then converted to analog with a Digital-to-Analog Converter (DAC), upconverted to a high carrier frequency and amplified using a High-Power Amplifier (HPA). The reception chain is constituted by a Low-Noise Amplifier (LNA), downconverter and an Analog-to-Digital Converter (ADC) and allows the transceiver to function as a receiver in the same frequency band. The existing SI reducing methods that enable IB-FDX can be divided in the categories shown in figure 2.2, which will be described individually in this section, along with some examples.

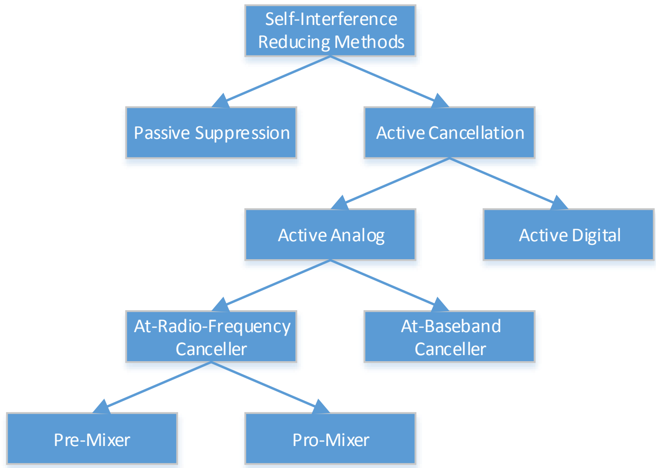


Figure 2.2: SI reducing methods. Adapted from [SPDS13].

2.2.1 Passive suppression

2.2.1.1 Antenna separation

Antenna separation is the simplest method of reducing SI. It consists in taking advantage of the attenuation generated from the physical distance d between the transmit and receiving antenna.

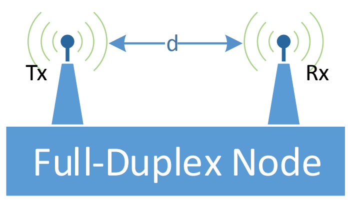


Figure 2.3: Antenna separation

This distance causes the transmitted signal's power density to decrease as it propagates through space. The resulting path loss can potentially suppress a decent amount of SI by itself: [DS10] reports that by simply separating the antennas by 20 cm led to a cancellation of 39 dB and separating them by 40 cm led to a cancellation of 45dB. While this suppression method is not good enough to make a robust system by itself, there is no reason not to exploit this convenient phenomenon in a two antenna scheme, as long as the terminal's design allows it. Therefore, antenna placement is an important topic to consider when designing a FDX system, as this allows to further increase the amount of Self-Interference Reduction (SIR).

2.2.1.2 Directional isolation

In directional isolation, directional antennas' coverage area is exploited in order to separate the beams of the transmitter and receiver. Directional antennas have a fixed beamwidth, measured in degrees, that illustrates the coverage area or radiation pattern of a particular antenna. This way, designs can be projected in a way that the gain of the transmit antenna is low in the direction of the receive antenna in order to reduce SI as in Rice's [ESS13].

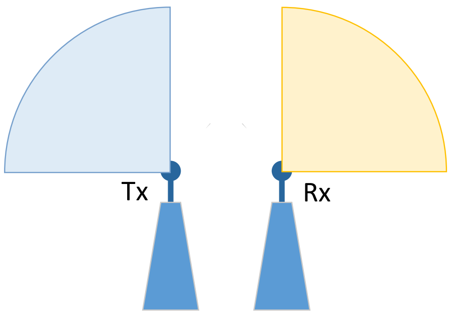


Figure 2.4: Beam separated antennas

2.2.1.3 Absorptive shielding

In absorptive shielding, SI is suppressed by placing a slab of Radio-Frequency (RF) absorber material between the transmitter and the receiver so that it inhibits the propagation of electromagnetic radiation. An example of this approach is Rice's [ESS13].

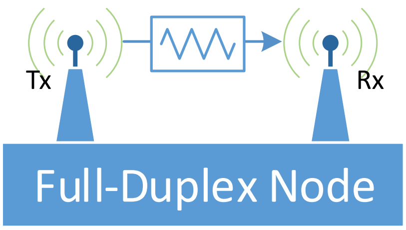


Figure 2.5: Theoretical scheme of a RF absorber

2.2.1.4 Cross-polarization

Cross-polarization consists in modulating the polarization of two waves in order for them to be orthogonal between them. Cross-polarisation can be linear (two waves polarised as horizontal and vertical) or circular (two waves polarised as right-hand circular and left-hand circular).
In theory, if the waves are polarised orthogonally, the interference between them is non-existent and it allows establishing two simultaneous links at the same frequency band. This is called frequency re-use and it has been used to increase the capacity on satellite networks systems, without increasing the bandwidth allocated. Unfortunately, imperfection of the antennas and depolarisation of the waves by the transmission medium leads to interference between the two links [MB02]. In [ESS13], a IB-FDX design is suggested that transmits with horizontal polarization and receives with vertical polarization.

2.2.2 Active cancellation

In active cancellation, a cancelling signal is generated by inverting the phase of the known interference signal and injected into the received signal in order to cancel its interference. Theoretically, a signal and its opposite cancel each other out perfectly, but the exact inverse of a signal is sometimes difficult to estimate because of phase noise, multi-path reflections and other random components of the received SI signal unknown to the canceller [SPDS13]. Active cancellation methods are also restricted by the limited dynamic range. The dynamic range refers to the range of the input signal levels that can be reliably measured simultaneously [HVK01]. Since the transmit and receive antenna are either the same or relatively close to each other, the signal passed to the analog-circuits can be above the dynamic range, which causes the measuring device to saturate, resulting in inaccurate estimations. The limited dynamic range affects non-ideal amplifiers, oscillators, ADCs, DACs and makes total cancellation impossible, even if the SI signal is perfectly known [DMBS12b].

2.2.2.1 Analog cancellation

Analog cancellation can be divided in two main categories, depending on where the cancellation occurs.
At-radio-frequency canceller
In an At-Radio-Frequency (At-RF) canceller the signal and its inverse are added at the carrier's frequency. At-RF cancellers can be subdivided based on where the cancellation signal is generated. A pre-mixer generates the cancelling signal prior to RF upconversion. An example of an pre-mixer is Rice's [DS10]. A post-mixer generates the cancelling signal after RF upconversion. An example of post-mixer is Stanford's [JCKBSSLKS11]. A block diagram of At-RF cancellers is shown in figure 2.6, where x_I denotes the SI signal, h_I denotes the SI signal after upconversion, f(.) denotes the pre-mixer's processing function and g(.) denotes the post-mixer's processing function.

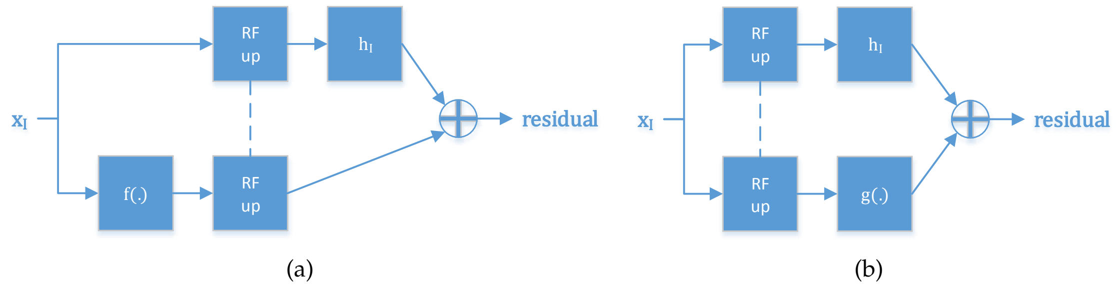


Figure 2.6: (a) pre-mixer architecture; (b) post-mixer architecture . Adapted from [ESS13].

A particular case of the post-mixer mechanism is the antenna canceller. In antenna cancellation, transmit antennas are positioned in a way so they destructively add at the receive antenna. The processing occurs At-RF and the signals transmitted by the antennas are the negative of each other [SPDS13]. Examples of designs that use antenna cancellation are Stanford's [CJSLK10] and Princeton's [AKSRC12].

At-Baseband Canceller

In an At-BaseBand (At-BB) canceller, the signal and its inverse are added at analog baseband frequency. This type of architecture is uncommon as the majority of the analog cancellation techniques occur in the At-RF stage. An example of an At-BB canceller is Rice's [KLA13]. A block diagram of At-BB cancellers is shown in figure 2.7, where x_I denotes the SI signal, h_I denotes the SI signal after upconversion and s(.) denotes the At-BB's processing function.

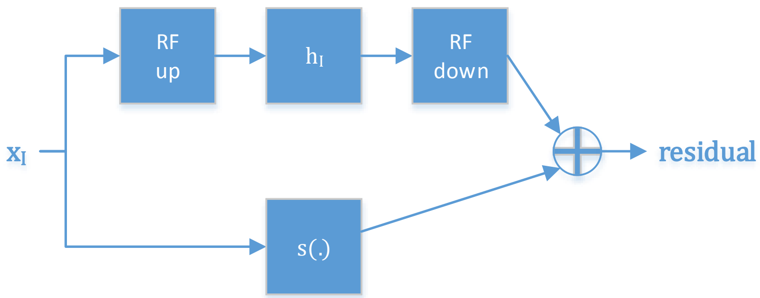


Figure 2.7: At-BB architecture. Adapted from [ESS13].

2.2.2.2 Digital cancellation

Unlike active cancellation methods, digital cancellation is only possible at digital baseband. As mentioned before, ADCs limit the effectiveness of these methods. If digital cancellation is used as a first step, the saturation is inevitable due to the relative magnitude of the interference. Even supposing that there is no front end saturation, the magnitude of the interference is far greater than the magnitude of the signal that we want to receive, which adds quantization noise due to the finite resolution of the analog-to-digital conversion [DS10; KR12; DSAJRRS14]. These two problems make digital cancellation

techniques unable to provide the suppression needed for a working IB-FDX system by themselves. Therefore, active digital cancellation is the final step of current designs, in order to avoid the saturation of the ADCs.
Digital cancellation is an essential component in the current FDX designs. Nearly every reported design uses this approach as it dispenses the addition of new components to the FDX transceiver. Some examples are Stanford's [BMK13; DS10] and Rice's [JCKBSS-LKS11].

2.3 Self-interference reduction overview

A logical approach to the challenge of creating FDX designs would be to combine every suppression and cancellation technique in order to achieve the highest SIR possible, assuming that each stage is independent of the stages prior to it. However, [Dua12] experimentally observed that this is not the case, leading to the conclusion that the total cancellation of a FDX system is not the sum of the maximum SI cancelled by each stage in isolation. It also suggests that when a stage cancels more SI, the next stages will cancel less.
According to [SPDS13], the phase noise associated with the local oscillators at the transmitter and receiver is responsible for three major issues:

1. It limits the amount of analog cancellation in a FDX system;
2. It makes the analog and digital cancellers depend on each other in a cascaded system;
3. It makes the passive suppression methods impact the amount of analog cancellation in pre-mixer designs.

In [SPDS13] it is analytically clarified the experimental results observed in [DS10; JCKB-SSLKS11; CJSLK10; Dua12; KSRZB11] and suggested that phase noise is one of the major bottlenecks in the current FDX designs. Therefore, improving phase noise characteristics in local oscillators can significantly improve the amount of active cancellation.
Passive suppression methods are mostly limited by not being able to address the reflected path (depicted in figure 2.8) [ESS13].
Active cancellation methods are mostly limited by RF impairments such as phase noise and limited dynamic range [ESS13; SPDS13; DMBS12b].
Active digital cancellation will only help cancel SI if the SI channel is not known perfectly [SPDS12]. In [DDS11] it is suggested that active digital cancellation should be used as a "safety net", for the frames where active analog cancellation achieves less than 32dB of cancellation. If it is not applied selectively, it can actually increase the amount of SI in the system.
Most designs use a concatenation of passive suppression and active cancellation in order to reduce the SI. While it is still not clear which approach is more effective [ESS13], all

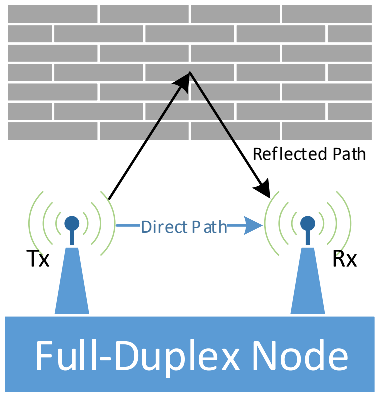


Figure 2.8: Reflected Path

studies seem to agree that passive suppression and active cancellation applied together will always result in superior SIR than just one of them.

2.4 Existing cancellation architectures

This section's goal is to compare and contrast the different designs and the SIR that each one of them can achieve.

2.4.1 Rice's designs

2.4.1.1 Rice's [DS10]

Uses off-the-shelf Multiple-Input and Multiple-Output (MIMO) radios to implement FDX communication. A model of the transceiver is shown in figure 2.9.

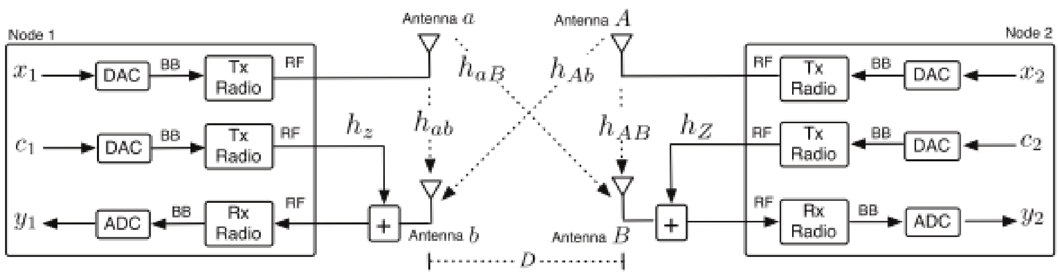


Figure 2.9: Model of the transceiver. Adapted from [DS10].

It is a simple pre-mixer design where x_i, c_i and y_i denote MT i's signal transmitted, canceller signal and desired signal respectively. Therefore, if $c_i = -(\frac{h_ab}{h_z})x_i$ the analog canceller achieves perfect cancellation. The average amount of SIR achieved by the different SIR mechanisms at 20 and 40 cm spacing between interfering antennas is depicted in table 2.1.

	Antenna separation	Antenna separation Digital cancellation	Antenna separation Analog cancellation	Antenna separation Analog cancellation Digital cancellation
20cm	39dB	70dB	72dB	78dB
40cm	45dB	76dB	76dB	80dB

Table 2.1: SIR achieved. Adapted from [DS10].

2.4.1.2 Rice's [ESS13]

Rice's [ESS13] exploited passive suppression to its fullest, by using antenna separation, absorptive shielding, directional isolation and cross-polarization. Moreover, analog and digital cancellation mechanisms were still employed after the passive suppression ones. This article measures an average of 70dB of SI suppression associated to the passive mechanisms and an average of 20dB to the active ones. It reports a maximum of 100dB SIR achieved with all techniques combined.

2.4.2 Stanford's designs

2.4.2.1 Stanford's [CJSLK10]

Stanford's [CJSLK10] design uses a combination of antenna cancellation, analog cancellation and digital cancellation to create a post-mixer transceiver that can apply FDX communications to IEEE 802.15.4 networks[1].
A block diagram of the transceiver is shown in figure 2.10.

The first stage of this design is the antenna cancellation. As shown in figure 2.10, if the wavelength of transmission is λ, and the distance of the receive antenna is d from one transmit antenna, then the other transmit antenna is placed at $d + \frac{\lambda}{2}$ away from the receive antenna, causing the signal from the two transmit antennas to add destructively. It is also essential that the signals' amplitude at the receiver match. Therefore, power splitters introduce 6dB attenuation in order for the power transmitted by Tx1 to be 6dB lower than the one by Tx2.
After the antenna cancellation stage, the transceiver applies its analog cancellation through the Qhx220 chip, a narrowband noise canceller. The QHx220 chip takes the known SI and received signals as inputs and outputs the received signal with the SI subtracted out.
Lastly, digital cancellation is applied by software, as soon as the signal is discretized by the ADC.
This article measures 20dB to 30dB of Self-Interference Cancellation (SIC) to antenna cancellation, 20dB of SIC to analog cancellation and 10dB of SIC to digital cancellation. It reports a maximum of 60dB SIR achieved with all techniques combined.

[1] Standard for Low-Rate Wireless Personal area Networks (LR-WPNs)

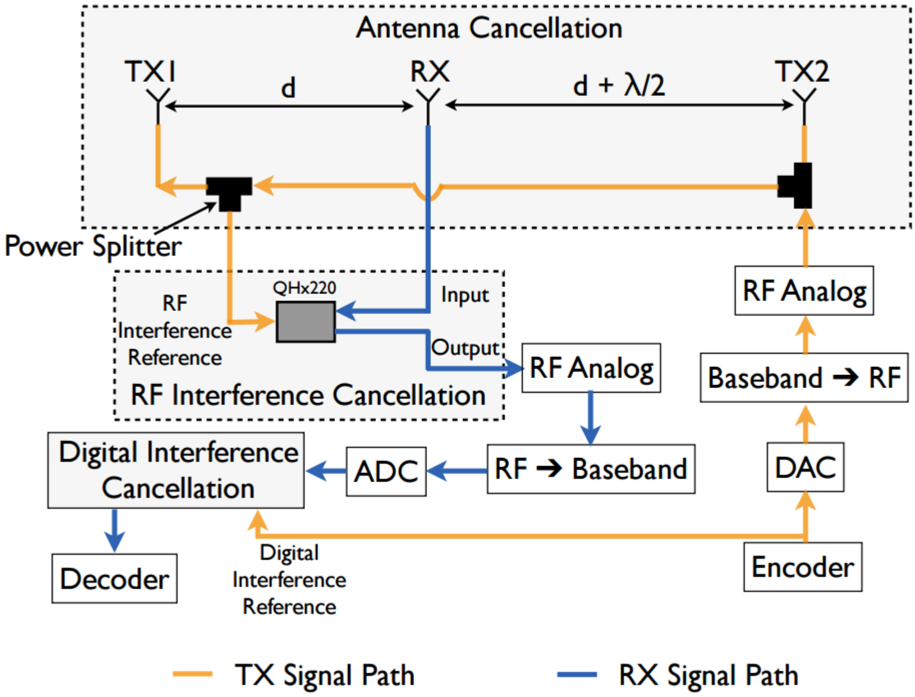


Figure 2.10: Block diagram of the transceiver. Adapted from [CJSLK10].

2.4.2.2 Stanford's [JCKBSSLKS11]

Stanford's [JCKBSSLKS11] design is a post-mixer transceiver that uses signal inversion and adaptive cancellation in order to achieve the required SIR for FDX communication. The idea behind this design is that any radio that inverts a signal through adjusting phase will always encounter a bandwidth constraint that bounds its maximum cancellation. Therefore, in order to achieve higher cancellation a radio needs to obtain the perfect inverse of the signal, thus the usage of a balun transformer. A block diagram of the transceiver is shown in figure 2.11.

The balun is used to obtain a good approximation of the perfect inverse of the SI signal and uses the inverted signal to cancel the interference. After the transmit antenna transmits the positive signal, the radio combines the negative signal with its received signal after adjusting the delay and attenuation of the negative signal to match the SI.
The phase and amplitude are adjusted by a tuning algorithm that allows the transceiver to quickly, accurately, and automatically adapt the FDX circuitry to cancel the primary SI component.
After this process the channel is estimated and the transceiver applies digital cancellation At-BB.
This article measures 43dB of SIC due to balun cancellation and 30dB of SIC to digital cancellation, achieving a maximum of 73dB SIR with both methods combined.

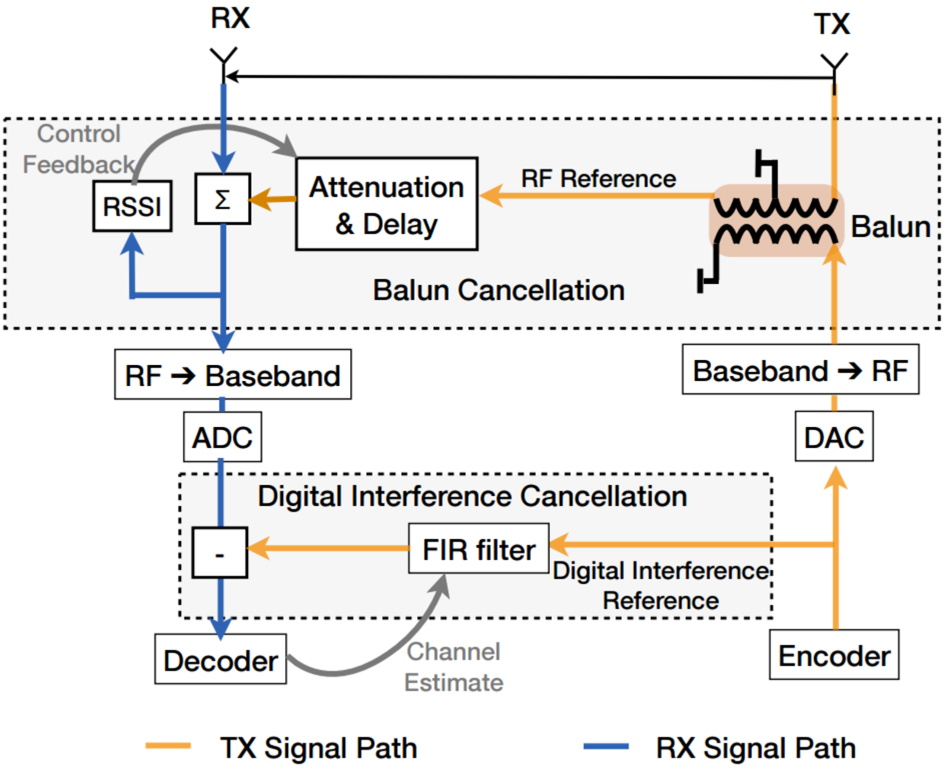


Figure 2.11: Block diagram of the transceiver. Adapted from [JCKBSSLKS11].

2.4.2.3 Stanford's [BMK13]

Stanford's [BMK13] design was the first implementation of an IB-FDX transceiver for IEEE 802.11ac[2]. It uses a single antenna for transmission and reception. A block diagram of the transceiver is shown in figure 2.12.

This design is classified as a post-mixer and uses a circulator in combination with a novel analog cancellation circuit to achieve a substantial amount of SIC. The circulator is used so that the transmission chain and the reception chain can share the antenna.

A copy of the transmitted signal is drawn from the transmission chain. The copy is passed through the analog cancellation circuit, which consists of parallel fixed lines of varying delays (wires of different lengths) and tunable attenuators. The lines are added up, and this combined signal is subtracted from the signal on the receive path. The cancellation circuit is based on a sampling and interpolation algorithm, where the weights of the linear combination are determined by using a standard algorithm called sinc interpolation.

In the end, digital cancellation is applied in order to clean out the remaining residual SI. This article measures at least 60dB of SIC to their novel analog cancellation circuit, 15dB of SIC to the circulator and 50dB of SIC to digital cancellation. It reports a maximum of 110dB SIR achieved with all techniques combined.

[2]Standard for high-throughput Wireless Local Area Networks (WLANs) on the 5Ghz band

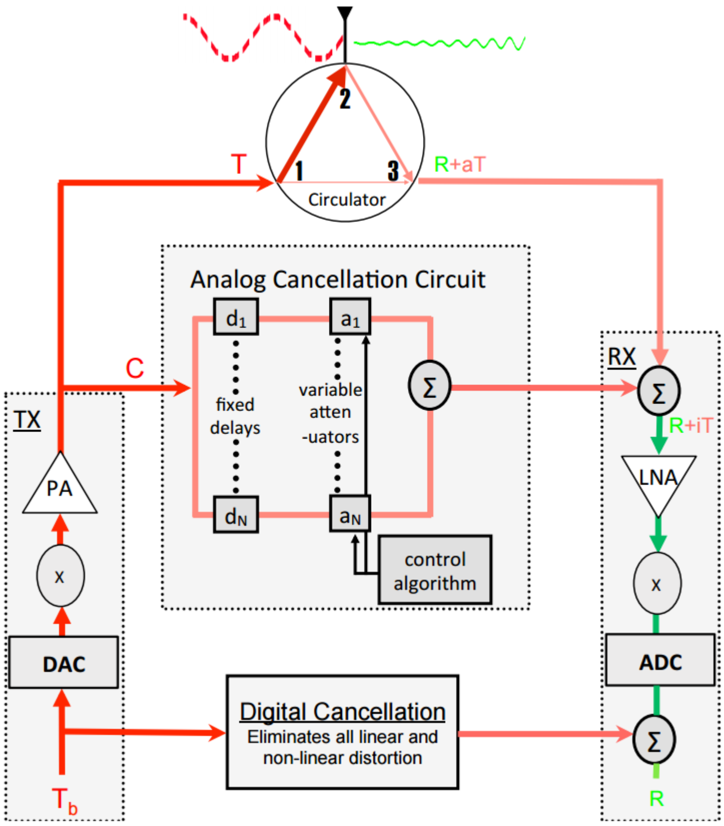


Figure 2.12: Block diagram of the transceiver. Adapted from [BMK13].

2.4.3 Princeton's design

[AKSRC12] reports the first MIMO FDX system for wireless networks. It classifies as a post-mixer and is called MImo full-DUplex (MIDU), using two level antenna cancellation to achieve the reported SIR.

In the first level, the two transmission antennas transmit at equal power and with a phase offset that causes the signal to add destructively at each reception antenna. After that, the signals received from the two reception antennas are further combined 180 degrees out of phase, providing the second level of antenna cancellation.

The placement of the antennas in this design is made as shown in figure 2.13(a). It is essential that the transmission and reception sets of antennas are on each other's perpendicular bisector. The perpendicular bisector is the perpendicular line that separates a pair of antennas at half the distance between the two antennas.

The reception pair of antennas need to be on the transmission's perpendicular bisector so that the signals add destructively (first level). On the other hand, the transmission pair of antennas need to be on the reception's perpendicular bisector so that combination of the unphased signals on the reception chain provides the desired signal (second level).

The symmetric antenna configurations can be extended to generic MIMO systems without the need for variable attenuators or delay elements (unlike Stanford's [CJSLK10], Stanford's [JCKBSSLKS11] covered in sections 2.4.2.1 and 2.4.2.2). In order to scale MIDU's

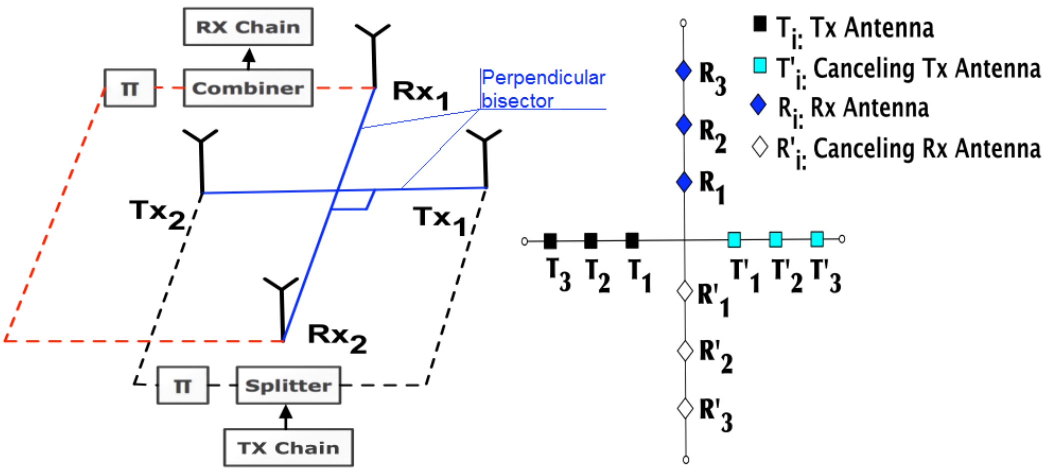


Figure 2.13: (a) MIDU's two level cancellation; (b) design scaled to MIMO. Adapted from [AKSRC12].

two level cancellation mechanism to a MIMO system an equal number of transmit and receive antennas are placed in a symmetric position on the opposite side of their respective axis as shown in figure 2.13(b).
This article reports a SIR of 45dB in an open-space indoor environment.

2.4.4 Comparison table

Table 2.2 shows a summary of the designs described and their reported performance. The first IB-FDX transceivers that were developed could only reduce SI by roughly 80dB. With recent advances the latest models manage to achieve around 100dB of total SIR.

Design	SIR methods used	Maximum SIR
Rice's [DS10]	Antenna separation Analog cancellation Digital cancellation	80dB
Rice's [ESS13]	Antenna separation Directional isolation Cross-polarization Analog cancellation Digital cancellation	100dB
Stanford's [CJSLK10]	Antenna cancellation Analog cancellation Digital cancellation	60dB
Stanford's [JCKBSSLKS11]	Balun passive cancellation Digital cancellation	73dB
Stanford's [BMK13]	Circulator Analog cancellation Digital cancellation	110dB
Princeton's [AKSRC12]	Two level antenna cancellation	45dB

Table 2.2: Comparison table

2.5 Full-duplex medium access control protocols

This section presents some of the FDX MAC protocols that have been developed by the scientific community. Most of the protocols proposed are additions and modifications of the current IEEE 802.11 standard. This is due mainly to the fact that it is easier to engineer a solution that can adapt to the current standard and allows backward compatibility.
Carrier Sense Multiple Access (CSMA) with Collision Detection (CD) methods distinguish themselves by being able to detect collisions in the medium and stop transmitting to save time and bandwidth. CD mechanisms are the basis of classic ethernet Local Area Network (LAN) and have satisfactory performance as long as it is possible to sense the entire medium.
In conventional wireless communication however, CD mechanisms do not work as well, since the range of a radio interface may not cover the entire system. Therefore, IEEE 802.11 establishes CSMA with Collision Avoidance (CA) as its MAC protocol. CA mechanisms are quite similar to CD's, except CA methods have backoff timers in order to avoid collisions and ACKnowledgement control packet (ACK) frames are used to infer collisions. In CSMA/CA collisions are undetectable, so the entire frame is transmitted even if a collision occurs [Tan10]. IB-FDX brings the possibility of using CSMA/CD in a wireless medium.
The protocols covered in this section can be sorted into two major groups: the ones that are optimized for single-hop networks and the ones that are optimized for multi-hop networks. Figure 2.14 depicts the two main types of topologies that can result from the adoption of IB-FDX at the network level: the relay and bidirectional topologies. Both topologies can be applied to either single-hop networks or multi-hop networks and have the potential to double the spectral efficiency and throughput.

Figure 2.14(a) depicts the relay topology, where node R acts as a relay for the single flow of data being sent from source node S to destination node D [SSGBRW14]. In HDX, 2 time slots are required for each packet to reach node D, whereas in FDX, every time slot can be used for node R to forward traffic without having to alternate between receiving from node S and transmitting to node D. For this scenario, only node R must possess IB-FDX capability. In a multi-hop network, the scenario presented in figure 2.14(a) can be extended in order to have n MTs relaying packets every time slot (provided all relays can operate in IB-FDX) as in $S \to R_1 \to \cdots \to R_n \to D$. This extension cannot be applied in single-hop networks since the Base Station (BS) or the AP is always the central node in the system.
Figure 2.14(b) depicts the bidirectional topology, where two data flows are active ($A \to B$ and $B \to A$). In HDX, each time slot is enough for one packet to reach its destination, unlike in FDX, where a time slot is enough for two packets to get delivered. For this scenario, both nodes A and B need to support IB-FDX [SSGBRW14].

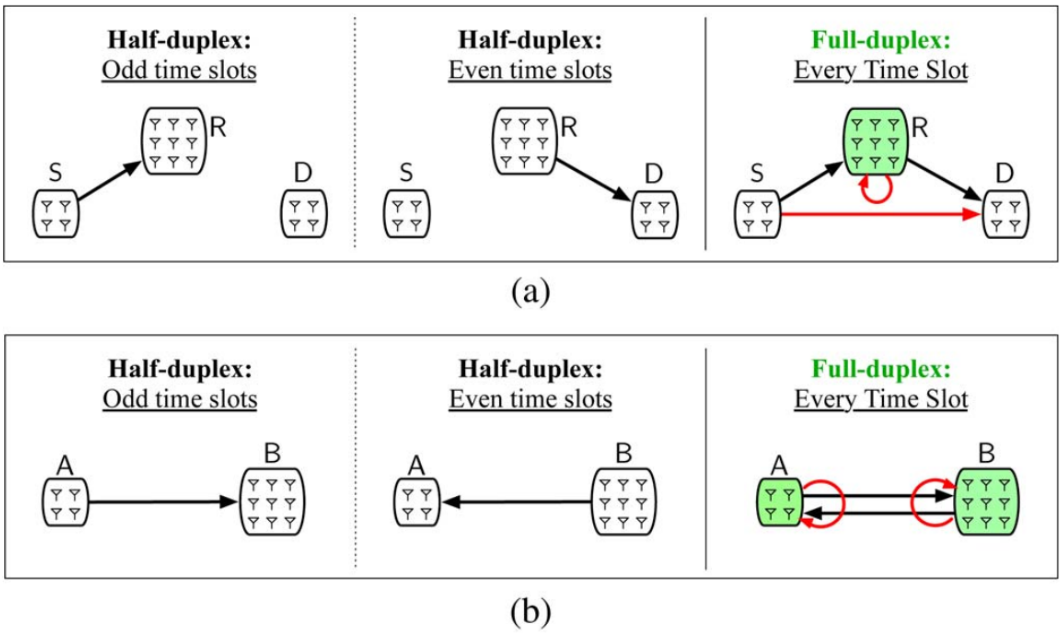


Figure 2.14: IB-FDX at the network level. (a) relay topology; (b) bidirectional topology. Adapted from [SSGBRW14].

2.5.1 Medium access control protocols optimized for single-hop networks (Infrastructure)

In a single-hop network, nodes communicate through a central AP. This means that the AP is always going to be either the source or the destination of the message being transmitted. This means that there can only be a maximum of two active flows at any given time [SPS11]. This assumption gives the AP the ability to control and regulate the other nodes' communication process.

2.5.1.1 Rice's Full-Duplex Medium Access Control

The Full-Duplex Medium Access Control (FD-MAC) [SPS11] uses the Rice's FDX transceiver architecture covered in section 2.4.1.1. FD-MAC builds on IEEE 802.11 and adds three new mechanisms in order to fully capitalize from the benefits of FDX.
Mechanisms

1. Shared random backoff;
2. Header snooping;
3. Virtual contention resolution.

Shared random backoff consists in coupling the backoff counter of two nodes that want to exchange messages. Typically when the medium is busy, each node chooses its own random backoff time, but because the purpose is for both nodes to communicate simultaneously with one another, they need to agree on a common backoff time.

Header snooping allows nodes to estimate the local topology. In order for this to work the nodes need to decode and examine the headers of all ongoing transmissions within radio range.
Virtual contention resolution's goal is to maximize the amount of FDX flows by using simultaneous communication whenever possible. This is done by making the AP look through multiple packets in its buffer and statistically deciding the one it's going to serve first.
Packet structure
Figure 2.15 depicts the FD-MAC's packet structure. The packets structure from IEEE 802.11 is adopted, where the PHYsical layer (PHY) header, payload and Cyclic Redundancy Check (CRC) fields are not modified. The MAC header is divided in two separate headers: the IEEE 802.11 MAC header and a novel Full-Duplex (FD) header. The FD header is divided in 6 separate fields. DUPMODE is a one bit field to distinguish a FDX packet from a HDX packet (denoted as Full-Duplex (FD) and Half-Duplex (HD)). Head-Of-Line (HOL) is a one bit field to indicate that the next packet in the buffer is for the destination of the current packet. DURNXT and DURFD are both 2 bytes long and their goal is to reveal the duration of HOL packet and the duration of the FDX exchange respectively. These two fields are optional, but relevant to counter the hidden node problem.
Clear-To-Send (CTS) is a one bit field that indicates that the destination of the current packet can send a packet to the source of the current packet. Lastly, the Shared Random Backoff (SRB) is a 10 bit field that indicates the common delay both nodes will wait before resuming FDX mode. Since both nodes transmit a packet with SRB field, the maximum value of the two is chosen.

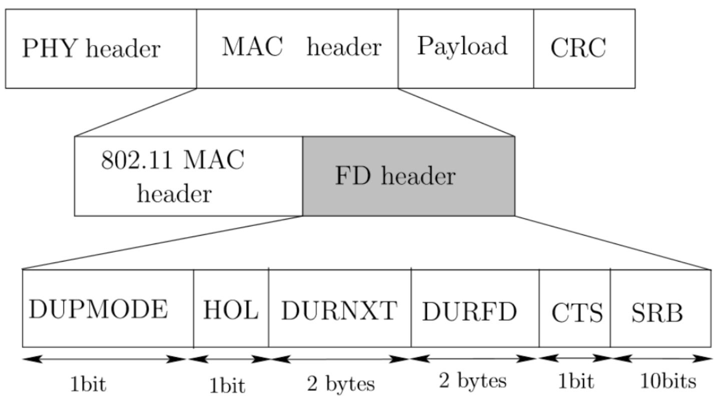


Figure 2.15: FD-MAC's packet structure. Adapted from [SPS11].

Timeline
Figure 2.16(a) depicts FD-MAC's timeline of events with one MT engaging in bidirectional communication ($AP \rightleftarrows M1$). In this example, the nodes contend for the medium and the AP wins the contention. It starts transmitting with *HOL = 1* since it has more packets in queue for M1. It sets *DUPMODE = HD* as the first packet in a two-way exchange for FD-MAC is always HDX. After receiving the DATA packet, M1 broadcasts

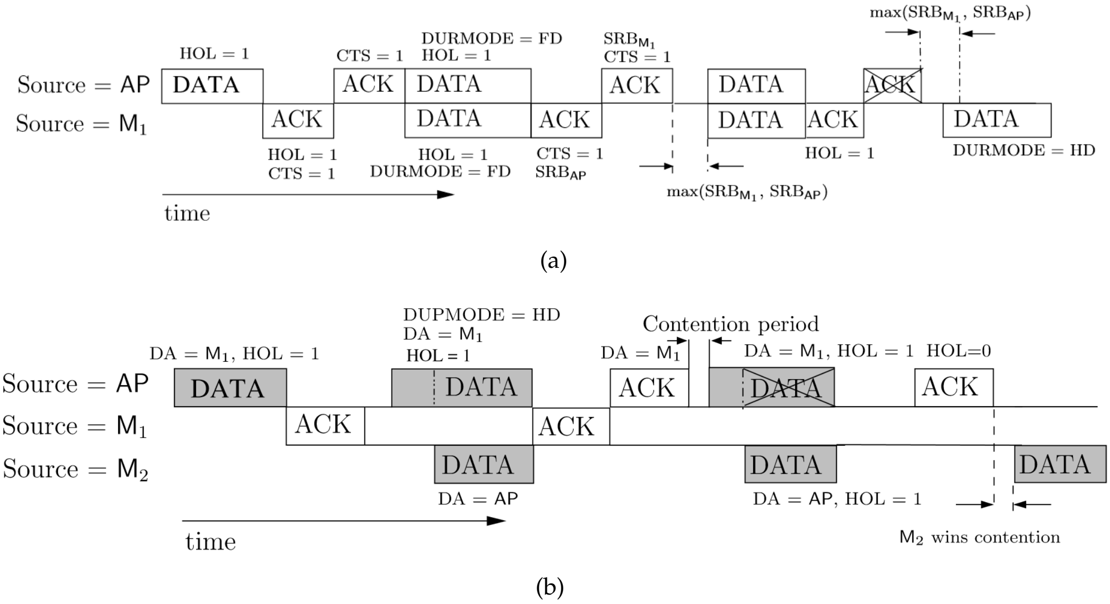


Figure 2.16: FD-MAC's timeline of events. (a) bidirectional communication; (b) relay communication. Adapted from [SPS11].

an ACK in order to confirm the reception of the packet and sets *HOL = 1* and *CTS = 1* to inform the AP that it wants to initiate a FDX communication. The AP responds with an ACK with *CTS = 1*, allowing M1 to start transmitting. AP and M1 engage in FDX packet exchange and once the DATA packets finish, they both confirm the reception by broadcasting an ACK. In this case, both nodes still have more packets in queue for each other, but they need to give other nodes the opportunity to transmit. In order to assure this, the AP and M1 set a common backoff time, given by the maximum value of the SRB field of both nodes. This allows them to skip the first two steps of the protocol (contention resolution followed by the transmission of one HDX packet). After the shared backoff time, both engage in FDX communication again, but the AP's ACK is not received properly by M1. This makes M1 purge its knowledge of the queue and contend for the medium at the end of two ACK periods after the DATA packet exchange finishes.
If the AP and the two MTs form a clique (M1 and M2 in radio range of each other), relay topology cannot be enabled due to the ITI. This concept will be covered with more detail in section 2.6. Therefore, figure 2.16(b) depicts FD-MAC's timeline of events where M1 and M2 are outside of each other's radio range since this is what allows them to engage in relay communications ($AP \rightarrow M1, M2 \rightarrow AP$ and $AP \rightarrow M2, M1 \rightarrow AP$). In this example, M1 does not have packets in queue, therefore it is only receiving. For M2 to engage in a relay communication, two conditions have to be met:

1. M1 cannot be in radio range of M2;

2. M1 cannot be engaging in a bidirectional communication with the AP.

In order for M2 to ensure condition 1, it waits for one ACK duration after the finish of the DATA packet from AP. If M2 does not receive the ACK, it assumes that M1 is not in radio range.
In order for M2 to ensure condition 2, it decodes the FD header of the DATA packet being sent by the AP. Since *DUPMODE = HD*, M1 will not transmit and M2 can start transmitting its packet to AP. For this transmission, the packet has to be fragmented so that M2's transmission ends before M1's ACK begins. In this case, one of the DATA packets that AP sent to M1 was not received properly, so M1 does not respond with an ACK making backoff synchronization impossible. Therefore, both nodes purge the information about the queue state, which makes the protocol return to its initial state (contention resolution).
These two conditions allows MTs to engage in FDX communications with the AP, but may cause collisions if there are more MTs out of range of the AP's destination. To solve this, each node that detects a FDX opportunity, only transmits its packet with probability p_i.
[SPS11] reports that FD-MAC achieves a throughput gain of up to 70% over HDX for identical transmit power.

2.5.1.2 Stanford's Janus

Janus [KMQKL13] is a innovative new MAC protocol, specifically designed to exploit FDX wireless capabilities. This protocol's notable traits are its ability to:

1. Identify all FDX opportunities;
2. Schedule packet exchange to maximize throughput;
3. Avoid collisions.

This protocol operates in cycles. At the beginning of each cycle, the AP broadcasts a probe packet. This packet signals all nodes registered under the AP to send the length of the packets they want to send. This exchange is done in a predefined order and allows the AP to identify the size of incoming packets and simultaneously collect information about the interference environment around each node. The interference information is stored in a table called conflict map and gives the AP an accurate picture of interference in the network, that allows it to identify which nodes can transmit simultaneously.
After receiving this information, the AP calculates the best possible combination of transmissions and the data rates of the transmissions. This centralized mechanism allows the AP to schedule transmissions in a way that completely eliminates collisions and maximizes throughput. This calculation is performed by the FDX scheduler using the information gathered by the replies of the MTs.
In order to avoid having a group of nodes with perfect FDX synergy starving other nodes, Janus implements a load control mechanism.

The throughput with Janus can be up to 2.5 times higher than its HDX alternative [KMQKL13]. However, maintaining an optimized schedule may require too many network and processing resources in a dynamic network with fast moving terminals.

2.5.2 Medium access control protocols optimized for multi-hop networks (Ad-hoc)

A multi-hop network is a decentralised type of network, with no pre-existing infrastructure, where each node participates in forwarding data for other nodes. The topology is assumed to be irregular and constantly changing.

2.5.2.1 Sophia's University full-duplex medium access control protocol

[MB12] proposes a novel line-type multi-hop MAC protocol that uses directional antennas' controllable directivity to mitigate interference. This type of scenario is highly applicable in wireless mesh networks and wireless sensor networks. It uses Stanford's FDX transceiver architecture covered in section 2.4.2.2.
This protocol intends to use FDX communication in order to enable relay switching, by creating a one-way flow of data traffic. An example of a operation using the proposed protocol is shown in figure 2.17.

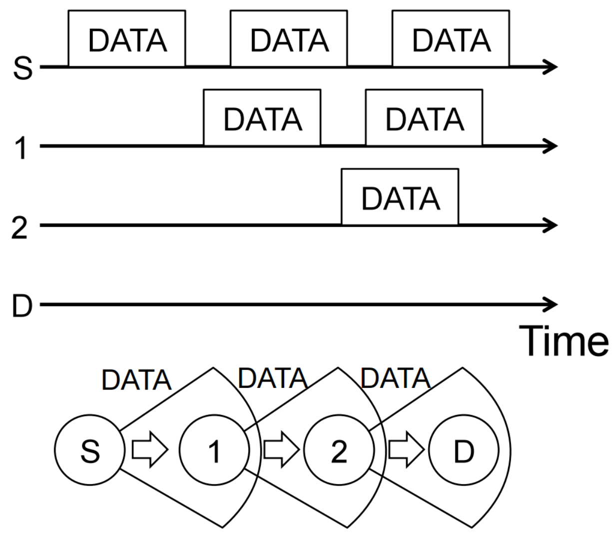


Figure 2.17: Operation with proposed protocol. Adapted from [MB12].

It builds on CSMA/CA without Request To Send (RTS)/CTS with three main modifications:

1. Modified condition for data transmission;
2. No acknowledgement frames;
3. No contention window.

The data transmission condition is modified so that a node is allowed to transmit data if it detects carrier and the destination MAC address of the detected data is the node itself. This is what allows the nodes to engage in two-way simultaneous communications. The reason given for the removal of the acknowledgement frame was that since the protocol assumed sophisticated routing protocols or topology controls were used, the ACKs were redundant and only caused collisions. The last modification has to do with the fact that data collisions hardly occur in line-type multi-hop networks. Therefore, this mechanism was removed from the protocol.
This protocol does not address possible errors that might occur due to channel noise generated from other devices. Given the lack of ACKs, the errors have to be addressed by mechanisms at higher layers (e.g. transport). [MB12] focus heavily on preventing and avoiding collisions, rather than resolving them.
This article reports that the protocol presented can improve end-to-end throughput up to 114% in such systems.

2.5.2.2 Wisconsin-Madison's full-duplex medium access control protocol

[XZ14] is an asynchronous MAC protocol. It allows a pair of FDX transceivers to contend for channel access and transmit packets independently, as if no mutual interference exists. This protocol builds on IEEE 802.11 standard, adding two specific features:

1. While in receiving mode, a receiver can continue sensing its channel status;

2. While in receiving mode, a receiver can transmit back to the sender if it senses an idle channel and finishes backoff.

With this protocol, it is not possible to synchronize the transmitter and receiver's MAC operations, therefore they need to contend for channel access independently.
Unlike the other protocols described, this protocol does not try to maximize the amount of FDX opportunities. Therefore, two-way simultaneous communications only occurs if their transmissions happen to overlap. An example of an operation using the proposed protocol is shown in figure 2.18.

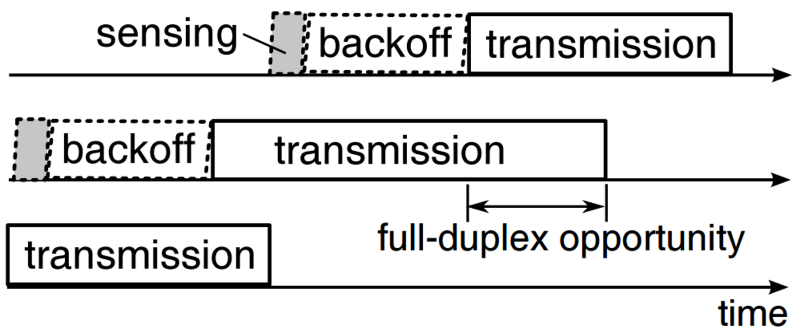


Figure 2.18: Operation with proposed protocol. Adapted from [XZ14].

This article reports an average throughput with this protocol 1.46 times higher than its HDX alternative, but it can reach up to 2.5 times higher.

2.6 Full-duplex and the inter-terminal interference

[XZ14] reported that while FDX has the potential to double the data rate within the cell's coverage range, having two MTs transmitting simultaneously translates into a wider interference region. This effect is shown in figure 2.19. This is called ITI and its representation is illustrated in figure 2.19.

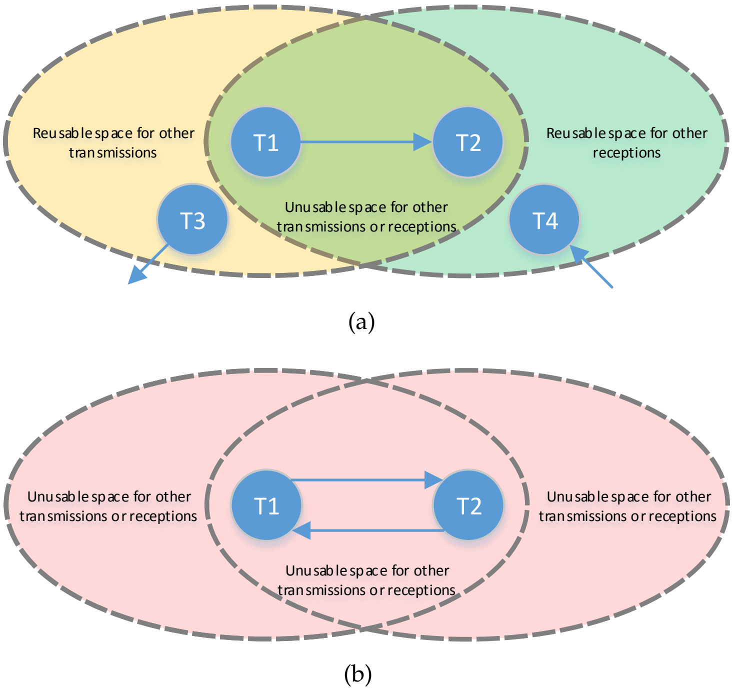


Figure 2.19: (a) spacial reuse for HDX; (b) spacial reuse for FDX. Adapted from [XZ14]

In HDX, since T1 is not receiving, other MTs can transmit inside its interference range. A similar concept applies to T2, as it is only receiving, other MTs can use that space to receive from other MTs. With FDX however, as both MTs are transmitting and receiving simultaneously, no other MTs are allowed to access the channel within their interference range.

A way to handle ITI is by using IB-FDX in a MPR system. A MPR system has the ability to receive more than one packet from multiple concurrent transmissions [LSW12], which means that it presents a strong synergy when combined with IB-FDX. Theoretically, in such a system, providing all MTs in the network support MPR, any MT can transmit regardless of its location and its interference range. Unfortunately, that would require MTs to have perfect knowledge of the network's topology, and perfect power control by all MTs, which suggests that it is infeasible given the current state of the art.

2.7 Multipacket reception

In a traditional communications system, simultaneous transmissions result in collisions, which degrade the network's throughput. These systems are classified as Single Packet Reception (SPR), which implies that receivers can only receive a packet from each source at a time. A MPR system however, allows a node to receive more than one packet from multiple concurrent transmissions. This way, it is possible to decode the packets that were transmitted, even if a collision occurred [LSW12].

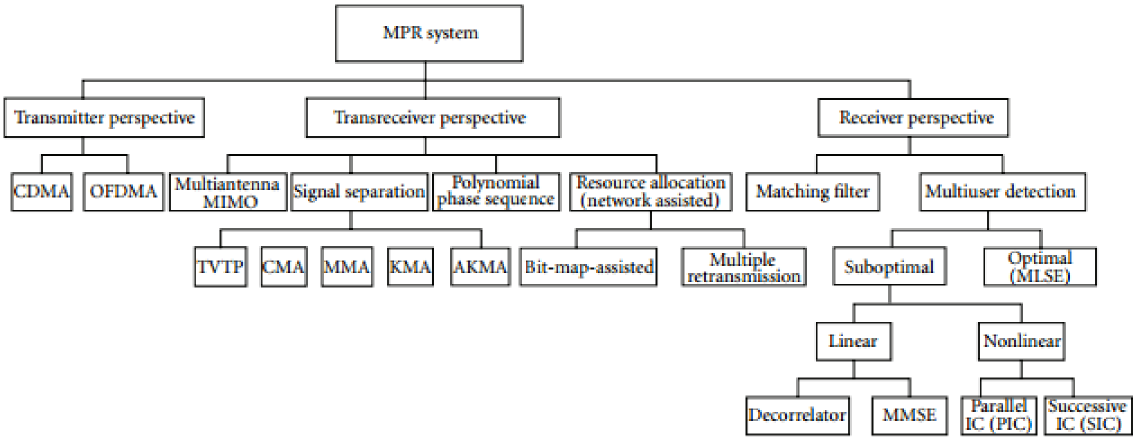


Figure 2.20: Classification of techniques applied for MPR. Adapted from [LSW12].

Many different technologies can be employed in order to enable MPR, classified in [LSW12]. Figure 2.20 divides MPR techniques into three main classes, which correspond to the place where the responsibility of enabling MPR lies. This classification is given based on transmitter, transreceiver, and receiver perspective.

2.7.1 Receiver perspective

The techniques used in this class completely shift the responsibility from the transmitters to the receivers [LSW12].
To employ the matching filter technique, the matched filter is calculated by correlating a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal [Doy09]. This technology is used extensively for SPR [LSW12], but its principles can also be applied to MPR, as in [CLBK04] where it is assumed that radio receivers devices are made of a bank of match filters that are able to decode each spreading code individually. This allows the receiver to receive packets concurrently from multiple sources without the need of having orthogonal spreading codes.
MultiUser Detection (MUD) is characterized by using information regarding code, timing, amplitude and phase in order to better detect each individual user [Mos96]. This technique became the de facto solution in order to enable MPR [LSW12], used in several MPR schemes [GLASW07b; WSGLA08; WGLA09; GLASW07a]. It is an elegant solution

in order to enable MPR as it lessens Multiple Access Interference (MAI) during the simultaneous transmissions on the same channel [LSW12]. A drawback to MUD is the requirement that the spreading codes of the multiple transmitters are known to the receiver *a priori* [Mos96].

MUD can be optimal or sub-optimal. Optimal MUD, despite being a excellent at demodulating the junction of multiple signals, has proven to be too computationally complex, increasing its complexity exponentially with the number of active users [Ver89]. Therefore, the scientific community has designed sub-optimal MUD techniques, that have a comparable performance relative to optimal MUD, but are computationally simpler. Sub-optimal MUD schemes can be divided into two categories: linear and non-linear.

In linear MUD, a linear transformation is applied to the soft outputs of the conventional detector, producing a new set of outputs, which are likely to have a better performance [Mos96]. Non-linear MUD schemes rely on interference estimators to remove the interference from the received signal before detection. Linear detectors should always achieve better results than non-linear detectors, but makes for a much more complex system [LSW12].

Nonlinear techniques can be divided in successive and Parallel Interference Cancellation (PIC). For this dissertation, successive interference cancellation will be referred as MultiPacket Reception by successive Interference Cancellation (MPR-IC). In MPR-IC it is required that the signals' power received at a given MT have enough separation between them. If this occurs, the concurrent transmissions are demodulated and cancelled allowing the serial resolution from the signal with the highest power to the one with the lowest power [XPWCL13; GDBO12]. On the other hand, PIC uses an estimate from the interfering bits from previous stages in order to enable the resolution of multiple packets [LSW12]. According to [LSW12], while PIC could support more simultaneous packets from different users it requires perfect power control, making MPR-IC a much simpler and practical solution in order to enable MPR.

2.7.2 Transmitter perspective

This set of techniques uses the transmitter as the critical piece in order to enable MPR. Techniques in this class revolve around separating different signals into orthogonal signalling dimensions in order to allow channels to be shared by multiple users. This is called multiplexing and the most used in MPR are frequency and code division multiplexing.

In Frequency Division Multiple Access (FDMA) the spectrum is divided into frequency bands, with each user having exclusive possession of some band in which to send their signal [Tan10]. Orthogonal Frequency Division Multiple Access (OFDMA) is one of the most popular FDMA techniques, widely used in wireless networks. OFDMA's main principle is to split the data stream to be transmitted onto a high number of narrowband orthogonal subcarriers by means of an Inverse Fast Fourier Transform (IFFT) operation

[BTFRM08].
Code Division Multiple Access (CDMA) is a form of spread spectrum communication in which a narrowband signal is spread out over a wider frequency band, allowing each user to transmit over the entire frequency spectrum all the time [Tan10]. For this, each bit time is subdivided into m short intervals called chips and each node is assigned a unique m-bit code called a chip sequence, known to the receiver *a priori*. During each bit time a node can transmit a 1 bit by sending its chip sequence and a 0 bit by sending the negation of its chip sequence. In order to resolve the content of the message, the receiver computes the normalized inner product between the received chip sequence and the chip sequence of the station it wants to receive [Tan10].

2.7.3 Transreceiver perspective

Techniques in this class are hybrid in the sense that use cooperation between transmitters and receivers in order to enable MPR. There are 4 main types of techniques that can be employed in this class: multi-antenna MIMO, signal separation, polynomial phase sequence and resource allocation. This dissertation will focus on resource allocation techniques since a variation of these methods is implemented in the presented system.
Network-assisted Diversity Multiple Access (NDMA) was first introduced in [TZB00] and it relied on storing collided packets in memory rather than being discarded. These packets are later combined with users' retransmissions in order to extract the collided information packets. Since this approach spreads the packet in time, it will be referred in this dissertation as MultiPacket Reception by Time diversity (MPR-T).
In NDMA [TZB00], for a collision of k users, k time slots are required to resolve the collision, therefore no channel slot is lost when a collision takes place. For this technique, it is mandatory that all users in the system possess a unique orthogonal IDentification (ID). This causes bandwidth inefficiency, especially with large user populations [TZB00]. This mechanism provided a novel signal processing-oriented viewpoint to the random medium access problem [TZB00] and was soon extended to several variants.
In [MV05] the Feedback-Free Network-assisted Diversity Multiple Access (FF-NDMA) was proposed which classified as a version of NDMA for uncoordinated ad-hoc networks. It was shown that retransmission diversity could improve the efficiency of random access, either in terms of energy, connectivity or bandwidth efficiency [MV05].
In [ZST02] a blind collision resolution scheme called Blind Network-assisted Diversity Multiple Access (B-NDMA) was presented. Blind techniques differ from original NDMA by removing NDMA's orthogonal sequence requirement. For this, an extra retransmission relative to training-based NDMA is necessary, but reduces packet length for the payload. This results in improved channel utilization and system capacity (especially with large user populations). B-NDMA determines the multiplicity by using a rank test method and resolves the packets by employing parallel factor analysis [ZST02].
[OD06] combined the minimum description length principle with a variation of the rank

test introduced for B-NDMA in order to create the Independent Component Analysis Network-assisted Diversity Multiple Access (ICA-NDMA). The algorithm consisted of two steps: first, the collision multiplicity is detected blindly and then the collision is resolved with independent component analysis. ICA-NDMA reports better detection performance than [ZST02] especially for low signal-to-noise ratio [OD06].

In [YYLLZ10] ICA-NDMA is extended into the Independent Component Analysis CooPerative Network-assisted Diversity Multiple Access (ICA-CooPNDMA) scheme. In this protocol, once a collision has been detected, the destination triggers the start of a cooperative transmission epoch. During each slot of cooperative transmission epoch, only one node is selected as relay to forward its received packet, so the energy consumption is reduced and the spatial diversity is obtained [YYLLZ10].

2.7.4 Hybrid solutions

Designs in this section use more than one of the techniques classified above.

2.7.4.1 Successive interference cancellation tree algorithm

This scheme uses two of the mechanisms described above. The Successive Interference Cancellation Tree Algorithm (SICTA) was first presented in [YG05] and its main goal is to omit slots that a standard binary tree could not. For that, it applies NDMA's concept of using collided packets to extract packet information (described in section 2.7.3) and the MPR-IC method (described in section 2.7.1). These MPR solutions allowed SICTA to reduce the number of slots used in standard tree algorithms, which resulted in a throughput improvement from 0.346 to 0.693.

2.7.4.2 Hybrid automatic repeat request network division multiple access

Hybrid automatic repeat request Network Division Multiple Access (H-NDMA) was first introduced in [GPBDOP11] and extended in [GPBDOP13]. It uses a cross-layered architecture to implement a slotted random access protocol with gated access. For this, [GPBDOP13] considers a structured wireless system, where the BS is a high resource device that runs the MPR algorithm with Hybrid Automatic Repeat reQuest (H-ARQ) error control in real-time. This BS controls the access to the channel by the MTs, which are low resource battery operated devices. H-NDMA [GPBDOP11] extends the original NDMA by adding additional retransmissions, for the packets that failed after an initial set of NDMA's k transmissions, for k colliding users. Eventually, H-NDMA may use less transmissions than k if the receiver is capable of separating the colliding signals with less transmissions. Therefore, it tolerates a lower signal reception power than the original protocol.

Figure 2.21 depicts H-NDMA reception scheme for a system with 2 MTs transmitting.

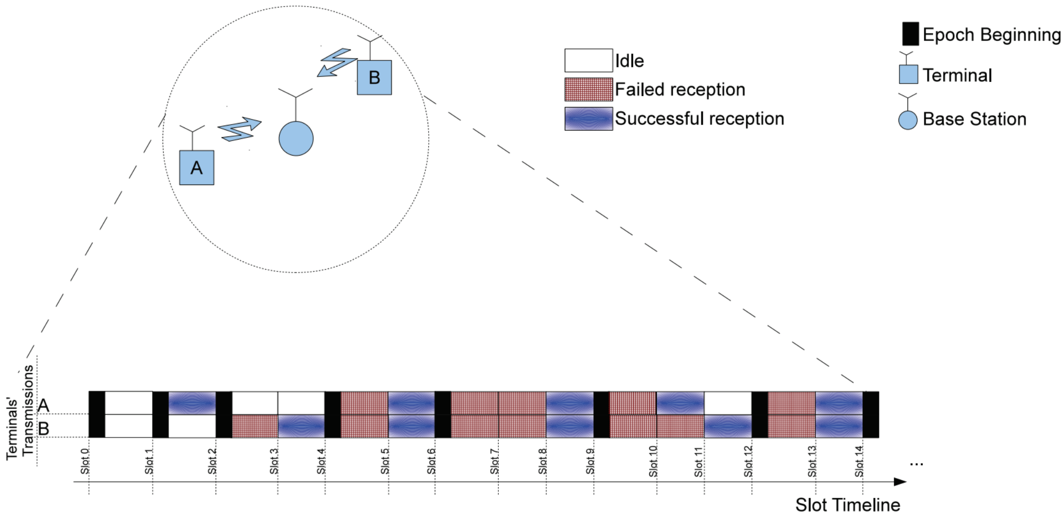


Figure 2.21: H-NDMA's reception scheme. Adapted from [GPBDOP13].

The uplink slots are organized as a sequence of epochs, which are delimited by SYNCronization control packets (SYNCs). The SYNC is broadcasted by the BS via the downlink channel and allows any terminal with data packets to transmit in the next slot. Terminals that do not transmit in the first epoch's slot are forbidden to send data until the next SYNC. At the end of each time slot, the BS detects collisions and either broadcasts a SYNC to signal the beginning of the next epoch (if no collisions occurred) or an ACK to signal a collision, defining which terminals should retransmit [GPBDOP13]. The epoch ends when all data packets are correctly received or after $P + R$ transmission slots, where P depicts the number of MTs that collided and R depicts the maximum number of H-ARQ retransmission slots.
The H-NDMA performance was evaluated for the Single-Carrier with Frequency-Domain Equalization (SC-FDE) receiver presented in [GDBO12] (analytically described in chapter 3).

3

Multipacket reception in the presence of in-band full-duplex communication

3.1 Introduction

This chapter starts by describing a single-hop LAN network where the AP runs a MPR receiver and supports concurrent reception of FDX and HDX communications, and where the MTs may support, or not, FDX. Secondly, a characterization of the influence of the FDX SIR's residual noise in the overall performance of the MPR system is given. This chapter extends the analytical model proposed in [GDBO12] for H-NDMA performance described in section 2.7.4.2, to account the effects of the residual SIR noise power. The model is then used to estimate the AP's coverage range for FDX and HDX communications, considering MPR-IC and MPR-T. The optimal average transmission power and coverage ranges are calculated for all MPR approaches considered, assuming a given generic FDX SIR attenuation. After this analysis, it is shown that the network's capacity can be improved by concurrently supporting simultaneously FDX and HDX MTs, using two different coverage ranges represented in figure 3.1. Lastly, the requirements for a MAC protocol that can manage such a system are presented.

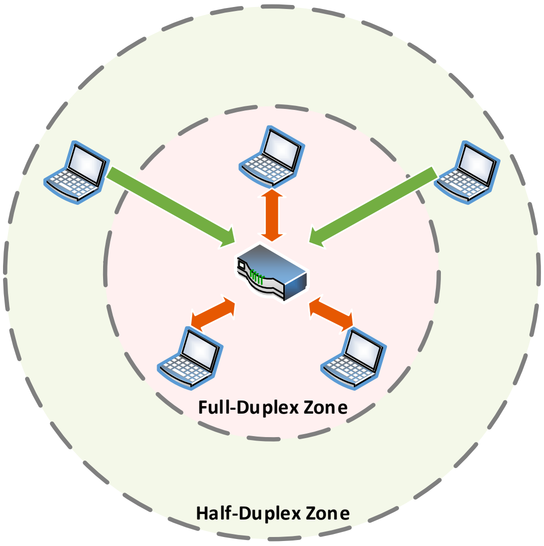


Figure 3.1: System model

3.2 System characterization

The considered system uses two types of MPR: MPR-IC and MPR-T, which were already described in 2.7. This system uses time scheduled transmissions to transmit data on separate channels, which may carry uplink only (i.e. from the MTs to the AP), downlink only (i.e. from the AP to the MTs), or simultaneous downlink and uplink traffic when a given MT supports FDX. Each channel is composed by a sequence of slots, which are assumed to have the length of one data packet. The AP controls the MT's transmission power, monitors the uplink Channel State Information (CSI) and defines the slot allocation schedule.

As in [LLR14], the FDX SIR residual noise is approximated by a null average Gaussian random variable with a variance equal to P_{SIR}. The ratio between the AP's transmission power ($P_{\mathrm{t}}^{\mathrm{AP}}$) and the average residual FDX SIR power (P_{SIR}) is

$$\beta = \frac{P_{\mathrm{t}}^{\mathrm{AP}}}{P_{\mathrm{SIR}}} . \tag{3.1}$$

3.2.1 Multipacket detection receiver performance

The implemented system considers SC-FDE [SKJ94] for the system's uplink, based on the uncoded Iterative Block Decision-Feedback Equalizer (IB-DFE) MPR receiver from [GDBO12] for an Offset Quadrature Phase-Shift Keying (OQPSK) constellation. The analytical expression for the Packet Error Rate (PER) in [GDBO12] is presented in this section and extended to account the FDX interference signal, considering the transmission from P MTs to one AP.

3.2.1.1 Single packet and multipacket detection receiver

As in [GDBO12], a data block of N symbols transmitted by a MT p is expressed in the time domain as $\{s_{n,p}; n = 0, ..., N-1\}$, and on the frequency domain as $\{S_{k,p}; k = 0, \ldots, N-1\}$. The received content at the AP by P MTs during L slots is $\{Y_k; k = 0, \ldots, N-1\}$ where $Y_k = \left[Y_k^1, \ldots, Y_k^L\right]^T$. This received content depends on the L transmissions of the MTs $H_k = [H_{k,1}, \ldots, H_{k,P}]^T$, where $H_{k,p} = \left[H_{k,p}^{(1)}, \ldots, H_{k,p}^{(L)}\right]$, the MTs' transmissions $S_k = \left[S_{k,1}, \ldots, S_{k,P}^L\right]^T$ and the channel's noise $N_k = \left[N_k^{(1)}, \ldots, N_k^{(L)}\right]^T$. To adapt [GDBO12]'s analytical model to a FDX system, the noise N_k was substituted by $N_k^{eq(r)}$, where r denotes the rth transmission. This noise is the result of the addition of the background thermal noise floor considered in [GDBO12], with the FDX SIR residual noise. The FDX SIR residual noise consists in two null average Gaussian random variables with a variance of

$$\sigma^2_{N^{eq(r)}} = \sigma^2_{N^{(r)}} + \beta^{-1}\sigma_s^2 \; . \tag{3.2}$$

Thus,

$$Y_k^{(r)} = \sum_{p=1}^{P} S_{k,p} H_{k,p}^{(r)} + N_k^{eq(r)}, \tag{3.3}$$

which can be expanded into the following system

$$\begin{bmatrix} Y_k^{(1)} \\ \vdots \\ Y_k^{(L)} \end{bmatrix} = \begin{bmatrix} H_{k,1}^{(1)} & \ldots & H_{k,P}^{(1)} \\ \vdots & \ddots & \vdots \\ H_{k,1}^{(L)} & \ldots & H_{k,P}^{(L)} \end{bmatrix} \begin{bmatrix} S_{k,1} \\ \vdots \\ S_{k,P} \end{bmatrix} + \begin{bmatrix} N_k^{eq(1)} \\ \vdots \\ N_k^{eq(L)} \end{bmatrix}.$$

The analytical model in [GDBO12] can be extended to resolve this equation and can be applied to any system where MPR-IC, MPR-T or any combinations of them are used. It can also be applied for SPR if only one MT is transmitting or by assuming that the channel response for the remaining users are part of the total noise. Therefore for a given terminal t the SPR noise equivalent (that accounts the other MT's signals) is calculated by

$$N_k^{H_k^r} = \sum_{p=1}^{t-1} H_{k,p} S_{k,p} + \sum_{p=t+1}^{P} H_{k,p} S_{k,p}, \tag{3.4}$$

given that $\sigma_S^2 = 1$, assuming valid the central limit theorem and that the signals transmitted are independent, results in

$$\sigma^2_{H_k^{(r)}} \approx \sum_{p=1}^{t-1} \left(H_{k,p}^{(r)}\right)^2 + \sum_{p=t+1}^{P} \left(H_{k,p}^{(r)}\right)^2, \tag{3.5}$$

which added to $N_k^{eq(r)}$ in equation 3.3 leads to the following model for the SPR system

$$\begin{bmatrix} Y_k^{(1)} \\ \vdots \\ Y_k^{(L)} \end{bmatrix} = \begin{bmatrix} H_{k,t}^{(1)} \\ \vdots \\ H_{k,t}^{(L)} \end{bmatrix} \begin{bmatrix} S_{k,t} \end{bmatrix} + \begin{bmatrix} N_k^{eq(1)} + N_k^{H_k^{(1)}} \\ \vdots \\ N_k^{eq(L)} + N_k^{H_k^{(L)}} \end{bmatrix}.$$

3.2.1.2 Iterative and linear receiver design

The IB-DFE receiver [GDBO12] runs N_{iter} iterations using the L transmissions to detect each of the P MTs. The estimated data symbol, $\tilde{S}_{k,p}^{(i)}$, for a given iteration i and MT p is given by

$$\tilde{S}_{k,p}^{(i)} = \mathbf{F}_{k,p}^{(i)\,T}\mathbf{Y}_k - \mathbf{B}_{k,p}^{(i)\,T}\bar{\mathbf{S}}_k^{(i-1)}, \tag{3.6}$$

where $\bar{\mathbf{S}}_k^{(i-1)} = [\bar{S}_{k,1}^{(i-1)}, \ldots, \bar{S}_{k,P}^{(i-1)}]^T$ denote the soft decision estimates from the previous iteration for all MTs, $\mathbf{F}_{k,p}^{(i)\,T} = [F_{k,p}^{(i,1)}, \ldots, F_{k,p}^{(i,L)}]$ are the feedforward coefficients,

$$F_{k,p}^{(i,l)} = \frac{H_{k,p}^{(l)\,*}}{\frac{\sigma_{Neq}^2}{\sigma_S^2} + \sum_{l=1}^{L}\left|H_{k,p}^{(l)}\right|^2}. \tag{3.7}$$

$\mathbf{B}_{k,p}^{(i)\,T} = [B_{k,p}^{(i,1)}, \ldots, B_{k,p}^{(i,P)}]$ are the feedback coefficients,

$$B_{k,p}^{(i)} = \sum_{l=1}^{L} F_{k,p}^{(i,l)} H_{k,p}^{(l)} - 1. \tag{3.8}$$

The coefficients are the ones that minimize the Mean Square Error (MSE) at the receiver. The error variance can be calculated using [GDBO12] and for a given MT p at the ith iteration is given by

$$\sigma_p^{2\,(i)} = \frac{1}{N^2}\sum_{k=0}^{N-1}\mathbb{E}\left[\left|\tilde{S}_{k,p}^{(i)} - S_{k,p}\right|^2\right] , \tag{3.9}$$

where $\mathbb{E}\left[\left|\tilde{S}_{k,p}^{(i)} - S_{k,p}\right|^2\right]$ can be calculated using [GDBO12]. The Bit-Error Rate (BER) of MT p at the ith iteration for a Quadrature Phase Shift Keying (QPSK) constellation is

$$BER_p^{(i)} \simeq \mathrm{Q}\left(\frac{1}{\sigma_p{}^{(i)}}\right), \tag{3.10}$$

where $\mathrm{Q}(x)$ denotes the Gaussian error function.
For an uncoded system with independent errors, the PER for a fixed packet size of M bits is given by

$$PER_p^{(i)} \simeq 1 - (1 - BER_p^{(i)})^M. \tag{3.11}$$

This model applies to iterative and linear receivers. A linear receiver is a special case of the IB-DFE, where the number of iterations $N_{iter} = 1$ (i.e. the backward loop in the receiver is not used).

Equation (3.11) provides a generic function that can be used to calculate the PER for any system given the channel response $\mathbf{H}_k$, the FDX SIR residual power reduction (β), the AP's transmitted power ($P_{\mathrm{t}}^{\mathrm{AP}}$) and the bit energy to noise ratio (E_{b}/N_0) for the signal received from each MT. The energy received from MT p during transmission l to the AP is modelled by the $H_{k,p}^{(l)}$ coefficients, which include the multiplication by the attenuation gain (related with the Path Loss (P_{L})). When a MT does not transmit, the channel coefficient value is set to zero.

3.2.2 Analytical performance model

This section quantifies the aggregate throughput for FDX with the MPR methods presented above. Considering a scenario where P MTs transmit to the AP, and the AP transmits to one or more MTs, the network capacity is defined by the maximum aggregate throughput that is achieved in the network. MPR-IC allows up to P streams to be received, and the average PER PER_p^{IC} of MT p can be calculated using (3.11). Given the FDX downlink average PER, denoted by PER^{FX}, the average aggregate throughput can be calculated using

$$S^{\mathrm{IC}} = \left(1 - PER^{\mathrm{FX}}\right) + \sum_{p=1}^{P} \left(1 - PER_p^{\mathrm{IC}}\right). \tag{3.12}$$

Assuming that the same spreading factor S_{f} is used for the uplink and downlink of a MPR-T scheme, the aggregate throughput is reduced by the factor S_{f},

$$S^{\mathrm{T}} = \frac{1}{S_{\mathrm{f}}} \left(\left(1 - PER^{\mathrm{FX}}\right) + \sum_{p=1}^{P} \left(1 - PER_p^{\mathrm{T}}\right) \right), \tag{3.13}$$

where PER_p^{T} denotes the average PER for the MT p. Given that $PER_p^{\mathrm{T}} \leq PER_p^{\mathrm{IC}}$ for the same network conditions (i.e. transmission power, fading and path loss), the preferred MPR method will depend strongly on the PER values.

3.3 Performance analysis

This section presents a performance analysis of the results from the simulations performed with the model described throughout this chapter. A SC-FDE modulation is considered with an Fast Fourier Transform (FFT)-block of N = 256 data symbols, a cyclic prefix of 32 symbols, longer than overall delay spread of the channel, using a bandwidth of 64 MHz. A FDX SIR of between 80dB and 110dB was considered. The simulations were performed in MATLAB considering a rich multipath channel and the P_{L} (dB) was given by

$$P_{\mathrm{L}}(d) = 16.9 \log_{10}(\mathrm{d}) + 32.8 + 20 \log_{10}(f_{\mathrm{c}}), \tag{3.14}$$

where d is the distance given in metres and f_{c} is the centre frequency given in GHz, which was set at 2.5GHz. This equation originates from the line of sight indoor hotspot scenario defined by the International Telecommunication Union (ITU) [Itu].
The average transmission power P_{t}^{p} associated to a E_{b}/N_0 value can be calculated using,

$$P_{\mathrm{t}}^{p} = \frac{E_{\mathrm{b}}}{N_0} - G_0 + P_{\mathrm{L}}(d) + \sigma^2_{N_0} + 10\log_{10}(M)[\mathrm{dBm}], \tag{3.15}$$

where M is the number of bits in a packet, G_0 denotes the antenna gain and $\sigma^2_{N_0}$ is the thermal noise for a bandwidth H. The antenna gain G_0 was set at 20dB and the thermal noise is given by $-174 + 10\log_{10}(H)$ dB.

3.3.1 Characterization of a single packet reception system

This section focuses on analysing the impacts the several parameters considered in the model have in the AP's reception capabilities for SPR. The considered scenarios are presented in figure 3.2, where blue lines depict the desired signal and orange lines the SI generated by the FDX.

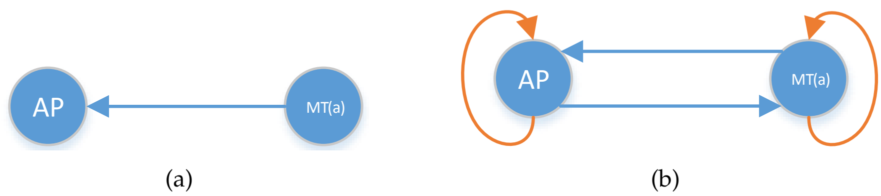
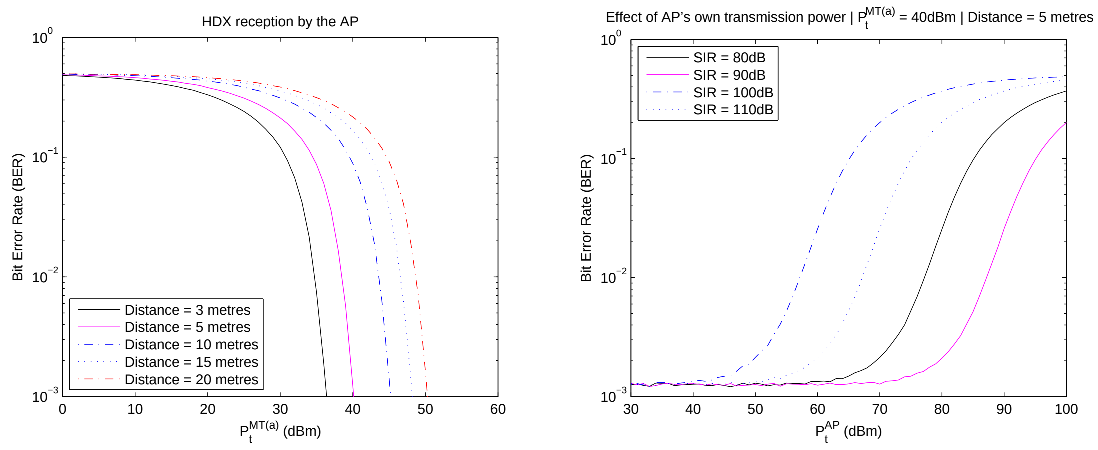


Figure 3.2: Performance cases for SPR. (a) HDX; (b) FDX

3.3.1.1 Bit error rate performance of half-duplex vs. full-duplex

Firstly, the performance of the HDX model for several distances is analysed. A diagram of this model is shown in figure 3.2(a) and its BER performance is shown in figure 3.3(a). Figure 3.3(a) depicts the BER for the AP's reception, over the transmission power used by MT(a), for several distances. As expected, increasing MT(a)'s average transmission power or decreasing the distance leads to a lower BER.
After analysing the performance of the HDX model, the effect of the AP's own transmission power $P_{\mathrm{t}}^{\mathrm{AP}}$ on its ability to resolve packets had to be considered. Therefore, the system shown in figure 3.2(b) was implemented, fixing MT(a) at 5 metres and an average transmission power of $P_{\mathrm{t}}^{\mathrm{MT(a)}} = 40$dBm. This configuration was chosen as it is enough to achieve a BER of 10^{-3} in HDX. Its results are shown in figure 3.3(b) and shows that having the AP transmitting while receiving, introduces a higher equivalent noise. The higher



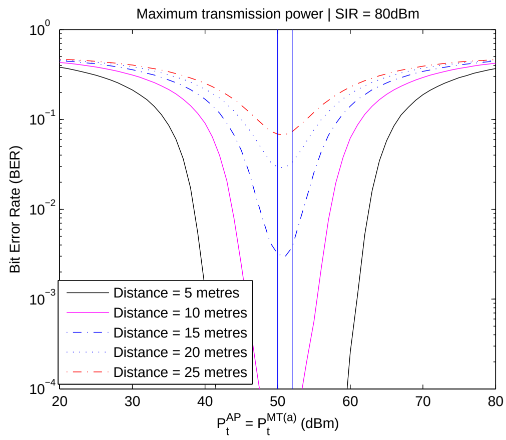
(a) (b)

Figure 3.3: BER performance over P_t.

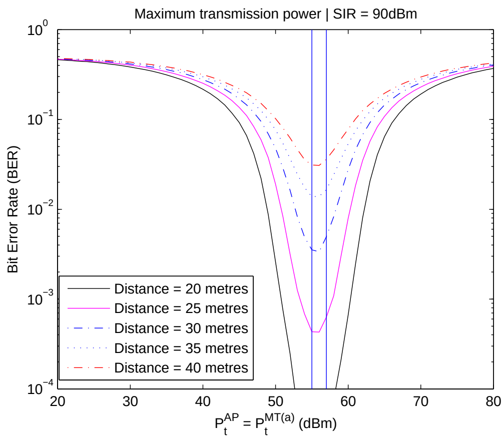
the power used by the AP in its transmission, the lower the Signal-to-Interference-plus-Noise Ratio (SINR) is going to be. This suggests that FDX introduces an upper limit to the AP's average transmission power, above which the reception fails. It also shows that a higher SIR leads to a higher upper limit.

Given this upper limit, a set of simulations were performed with the AP transmitting with the same average power as MT(a). This allows the determination of the maximum transmission power that can be used by the AP and MT(a) so both can reach each other. The results are shown in figure 3.4, which presents the BER for the AP's reception, over the transmission power used by the AP and MT(a), for several distances and SIR values. These plots present two important conclusions about the FDX system. Firstly, is that there is a particular set of values for P_t^{AP} that minimizes the BER for each value of SIR. This optimal power is usually between two values (blue vertical lines) and is closer to the lower bound for lower distances, and closer to the higher bound for higher distances. A second conclusion is that there is a maximum distance between the AP and the MT for each value of SIR, above which packet resolution becomes impossible, regardless of their average transmission power. A higher SIR allows for higher average transmission power, which in turn allows the AP and the MT to be farther apart while still being able to successfully receive packets. This maximum separation concept will be explored with more detail in sections 3.3.1.2 and 3.3.2.4. With this analysis, table 3.1 can be constructed, which contains the optimal average transmission power the AP or a MT can transmit in a FDX communication to still be able to resolve the packets that are being sent.

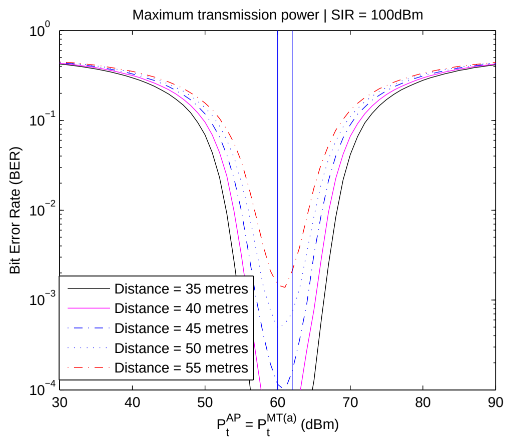
For the rest of the simulations presented in this chapter, the highest amount of optimal transmission power P_t was considered ($P_t = 52, 57, 62$ and 67dB respectively for a SIR of 80, 90, 100 and 110dB).



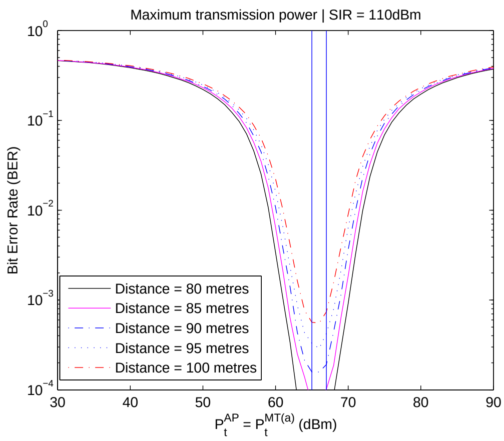
(a)



(b)



(c)



(d)

Figure 3.4: SPR BER performance over $P_{\mathrm{t}}^{\mathrm{AP}} = P_{\mathrm{t}}^{\mathrm{MT(a)}}$ for various distances and SIR values.

SIR (dB)	Optimal P_{t} (dBm)
80	50-52
90	55-57
100	60-62
110	65-67

Table 3.1: Optimal P_{t} for each SIR value.

3.3.1.2 Full-duplex coverage range for single packet reception

An illustration of the effects that a transmission at optimal power has on the AP's ability to resolve packets is shown in figure 3.5.

Figure 3.5 shows the AP's BER in a FDX communication (receiving and transmitting at the optimal power allowed for each SIR value), contrasting with the AP's BER in a HDX

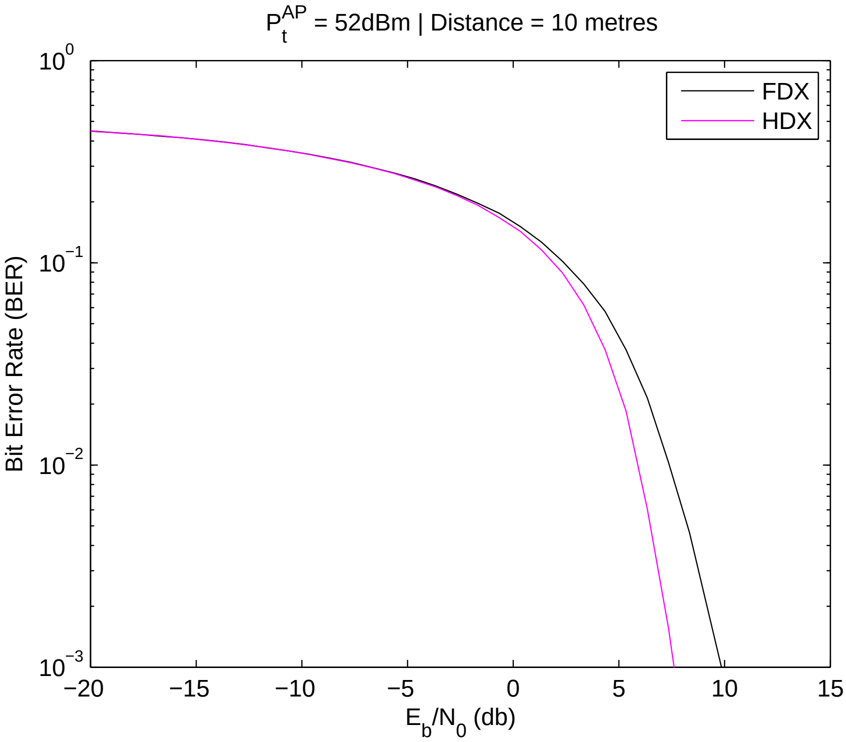


Figure 3.5: Comparison between HDX and FDX's BER performance over $\frac{E_B}{N_0}$.

communication. It suggests that whenever the AP is transmitting and receiving simultaneously, a higher reception power ($\frac{E_B}{N_0}$) is always required in order for the AP to be able to successfully receive the packets being sent. Since the MTs considered can also be FDX, they use an equivalent analytical model and the same can be concluded for them. This way, the system view depicted in figure 3.1 can be modified in order to add the Semi Full-DupleX (S-FDX) zone. The S-FDX zone allows a MT that is not transmitting to receive packets from the AP. This means the AP can still transmit to a S-FDX MT while receiving packets from other sources. It is important to point out that a MT inside S-FDX is still a HDX MT. A representation of this optimization is shown in figure 3.6(b).

Figure 3.6(a) depicts the model this chapter started by describing and figure 3.6(b) depicts the extended model. Note that S-FDX zone uses part of the HDX zone from the original model. In figure 3.6(b) only MT(b) is considered a S-FDX MT since it is the only one that is within the S-FDX radius and is not transmitting, which means that if the AP has a packet in queue for MT(b) it can be transmitted.

In order to determine the zones' radius for each SIR, a set of simulations were ran to calculate the minimum power that a MT needs to use in order to successfully reach the AP. For these simulations, it was assumed that the AP always uses its optimal power for each SIR depicted in table 3.1, except when it is not transmitting (HDX). This is not always the case since the AP can transmit with a lower power if its destination is at close quarters, but allows the determination of a MT transmission power that can be used regardless of the AP's own transmission power.

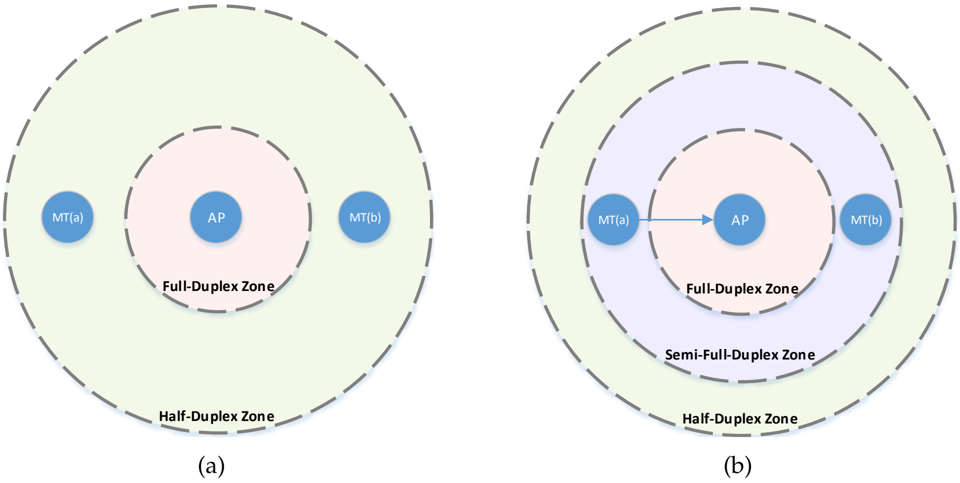


Figure 3.6: (a) plain model; (b) extended model.

For this set of simulations, a maximum PER of 1% was forced and the transmission power was calculated for distances between 3 and 100 metres, considering the line of sight indoor hotspot model defined by ITU [Itu]. The results are shown in figure 3.7 and presented in tables A.1, A.2, A.3, A.4 and A.5 depicted in appendix A.

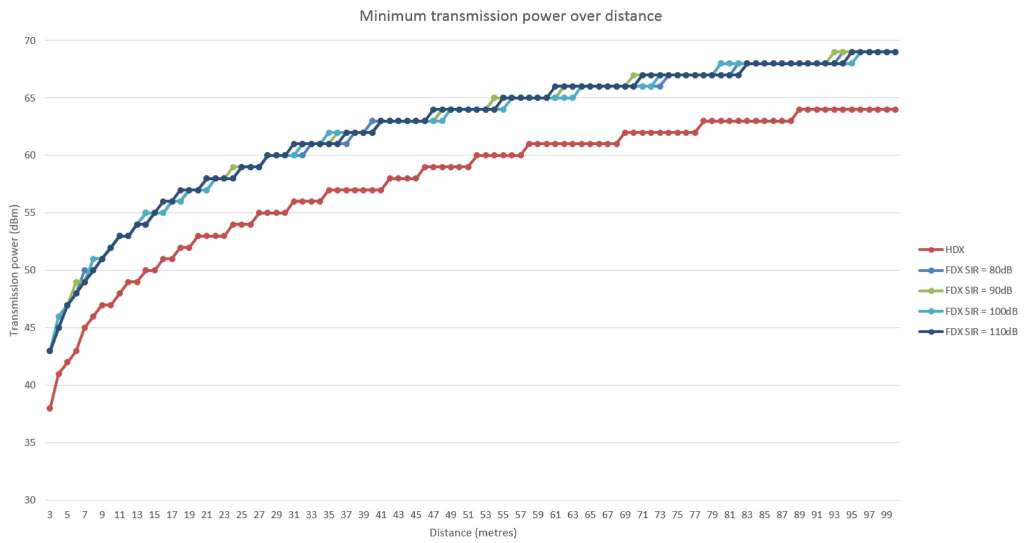


Figure 3.7: Minimum transmission power for a PER below 1% over distance, for a line of sight indoor hotspot model [Itu].

Figure 3.7 shows that despite having a transceiver with a higher SIR, roughly the same levels of power are required at the MT's end in order to achieve the same successful packet reception ratio. If the AP does not transmit, a lower level of power can be used and still ensure a successful reception. Since the MTs considered are also FDX, they use an equivalent analytical model and the same can be concluded for them, so the tables determined by this set of simulations can be used to determine the zones' radius. The radius are calculated by looking up in the table the farthest the optimal power (given by table 3.1) can reach for each SIR value. Its results are presented in table 3.2. HDX's radius is set at the model's maximum distance because the transmission power is not bounded (except by the limits imposed by the spectrum regulator) as the AP is not receiving.

SIR (dB)	Zones' radius (metres)		
	FDX	S-FDX	HDX
80	10	19	100
90	21	40	100
100	40	78	100
110	82	100	100

Table 3.2: Zones' radius for each value of SIR.

The S-FDX zone is not going to be considered in the simulation results presented below as the scenarios that were implemented focused on measuring the aggregate throughput with all MTs transmitting. However, this mechanism takes an important role in the design of the MAC protocol, presented in chapter 4.

3.3.2 Characterization of a multipacket reception system

This section analyses the impacts the several parameters considered in the model have in the AP's reception capabilities for MPR, along with a comparison with the SPR system considered in the previous section. The considered scenario is presented in 3.8, where the yellow line depicts the ITI.

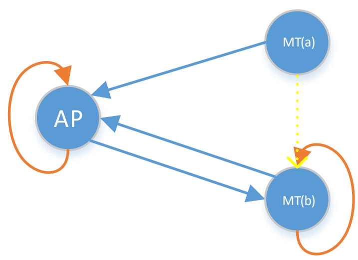


Figure 3.8: Performance case for MPR

3.3.2.1 Average and maximum number of transmissions

Since using MPR-T spreads the packets in time, a set of simulations were ran in order to determine the average avg_{TX} and maximum number of transmissions max_{TX} required to successfully receive all packets, given a number of concurrent MTs transmitting. For this set of simulations, the AP transmits at 52dBm, has a SIR of 80dB and the MTs transmit with the minimum power required for a successful reception by the AP in the first slot, given by the tables depicted in appendix A and represented in figure 3.7. Since all MTs reach the AP with the same average power, the only parameter that affects the number of transmissions required is the amount of MTs that are transmitting concurrently, so the tables are roughly identical for HDX and FDX with a SIR of 80, 90, 100 and 110. A total of 1000 iterations were ran for the calculation of each value. The measured results are shown in table 3.3.

Number of MTs	avg_{TX}
1	1.0060
2	2.0000
3	2.4560
4	3.0000
5	3.9990
6	4.0280
7	5.0000
8	5.7990
9	6.0010
10	6.9980

(a)

Number of MTs	max_{TX}
1	2
2	2
3	3
4	3
5	4
6	5
7	5
8	6
9	7
10	7

(b)

Table 3.3: (a) Average number of transmissions required; (b) Maximum number of transmissions required.

3.3.2.2 Power separation

In order to enable MPR-IC, the MTs' signals received at the AP need to have different powers with enough separation between them to allow the serial resolution from the signal with the highest power to the one with the lowest power. This power offset between the reception power of the MTs ($\frac{E_B}{N_0}$) is denoted by γ. In order to determine the minimum value of γ that enabled the successful operation of MPR-IC, a set of simulations were ran for each SIR, that iteratively lowered the power that the AP received from MT(b) until a maximum BER of 0.1% was reached, for an offset γdB. The values measured for γ were 12dB and 14dB, respectively for an AP operating in HDX and FDX.

3.3.2.3 Bit error rate performance for a full-duplex multipacket reception system

After analysing how the AP reacted to SI in a SPR system in section 3.3.1, a second MT was added in order to analyse the AP's reaction to SI with MPR-IC and MPR-T. An illustration of this scenario can be shown in figure 3.8 and its BER performance is shown in figure 3.9.

As characterized in chapter 2, MPR-IC uses the differences in the packets' reception power to separate and resolve them, while MPR-T exploits time redundancy by scheduling the packet spreading in time. Although not conventional, a SPR scheme can also use time redundancy, which is denoted by Single Packet Reception by Time diversity (SPR-T). Plots in figure 3.9 depict the BER performance of HDX (figure 3.9(a)) and FDX (figure 3.9(b),(c),(d)), for SPR ($MT = 1$, $L = 1$), SPR-T ($MT = 1$, $L = 2$), MPR-IC ($MT = 2$,

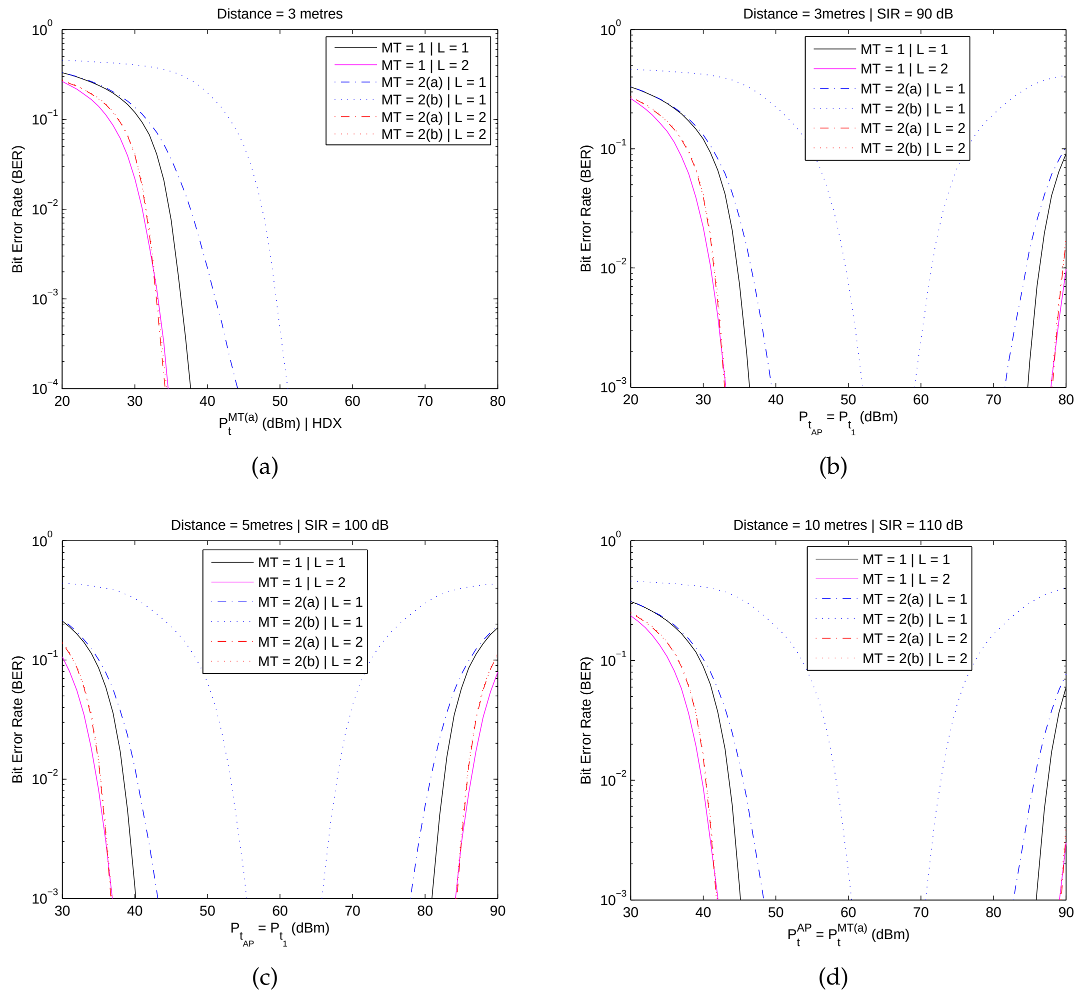


Figure 3.9: SPR, MPR-IC and MPR-T BER performance over $P_{\mathrm{t}}^{\mathrm{AP}} = P_{\mathrm{t}}^{\mathrm{MT(a)}}$ for HDX, FDX, various distances and SIR values.

$L = 1$) and MPR-T ($MT = 2$, $L = 2$). Equal reception power is assumed for MT(a) and MT(b) for MPR-T, and a power offset γ is considered between the reception power of MT(a) (the highest power) and MT(b) (the lowest one) equal to 12dB and 14dB, respectively for HDX and FDX. In the results depicted in figure 3.9, the AP always transmits with the same average power as MT(a), $P_{\mathrm{t}}^{\mathrm{AP}} = P_{\mathrm{t}}^{\mathrm{MT(a)}}$.

For HDX (figure 3.9(a)), it is possible to define a minimum average transmission power $P_{\mathrm{t}}^{MT(a)}$ value for each MPR type, above which the BER is below a given BER threshold. This threshold is higher for MPR-IC, especially for the MT(b). This is due to the fact that the power ($\frac{E_B}{N_0}$) received from MT(b) at the AP needs to be 12dB lower than the one received from MT(a). Due to residual errors from interference cancellation reception, MPR-IC has a higher BER than SPR, and time redundant methods (SPR-T and MPR-T) present the lowest set of BERs.

For FDX (figures 3.9(b),(c) and (d)), the same conclusions apply. Time redundant methods (SPR-T and MPR-T) provide the lowest BER and MPR-IC is the one that presents the highest, especially in MT(b) (this time with a reception power offset of 14dB). As in 3.3.1, a higher FDX SIR allows the AP to resolve packets from longer distances. With a SIR of 90dB, MPR-IC can only achieve FDX communication at 3 metres, while with a SIR of 100 and 110dB, these distances increase to 5 and 10 metres respectively.

3.3.2.4 Full-duplex coverage range for multipacket reception

The FDX AP's coverage range is the maximum distance where a MT can receive a FDX transmission from the AP with a fixed bounded average PER. Unlike the approach done in section 3.3.1.2, this was calculated by depicting the throughput over the distance, considering the conditions specified in section 3.3.1.1. These considered a scenario with 2 MTs, but other experiments not reported here showed that these values can be extrapolated to larger number of MTs. This hypotheses is confirmed by the good performance achieved with the proposed system with up to 10 MTs (presented in section 4.3).

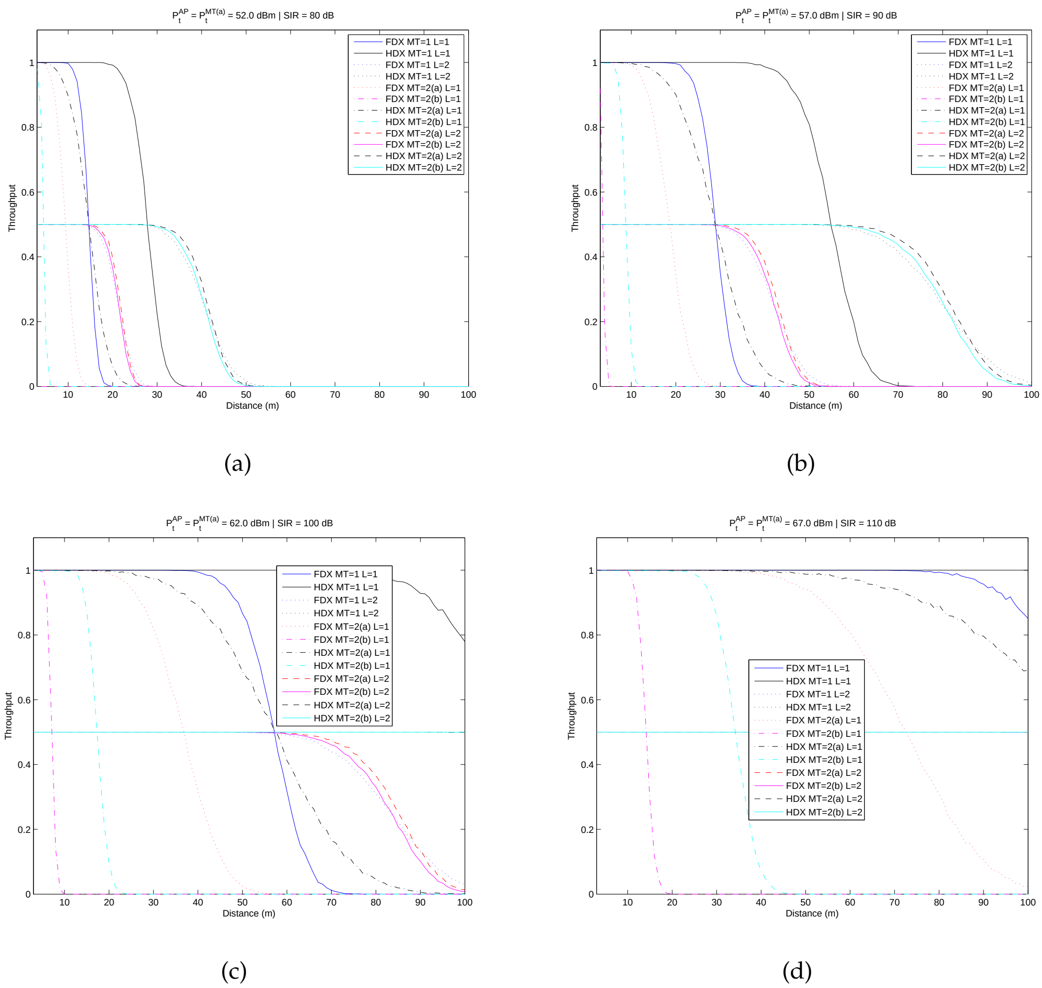


Figure 3.10: SPR, MPR-IC and MPR-T throughput for HDX and FDX with several SIR values.

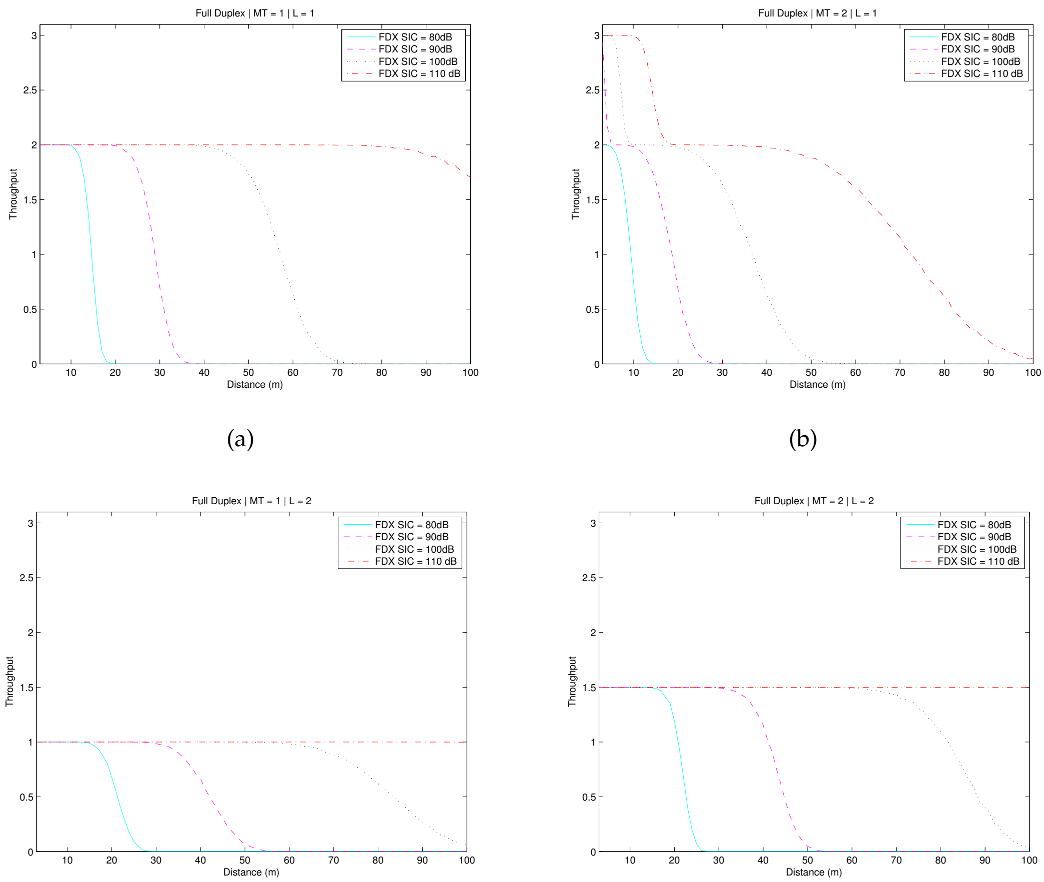
The average transmission power for the AP, MT(a) and MT(b) are equal for SPR, and

MPR-T, which were set at the optimal average transmission power for each SIR, given by table 3.1. Equal reception power is assumed for MT(a) and MT(b) for MPR-T, and a power offset γ is considered between the power of the signal received from MT(a) (the highest power) and from MT(b) (the lowest one) equal to 12dB and 14dB, respectively for HDX and FDX. Assuming equal flow rates for all links, normalized to one, SPR and MPR-IC ($L = 1$) have a maximum throughput of 1 and time redundant methods (SPR-T and MPR-T: $L = 2$) can only achieve a maximum throughput of 0.5 since having a retransmission translates into the reception of half the packets in the same time interval. As in 3.3.1.2, the AP's coverage range is a function of the FDX SIR value. The absolute values for SPR depicted in 3.2 can be visually confirmed by the SPR plots (FDX $MT = 1, L = 1$ for the FDX border and HDX $MT = 1, L = 1$ for the S-FDX border). Since the power levels being used are the same for FDX and HDX (even though the HDX average transmission power can be increased as explained in section 3.3.1.2), the maximum HDX range is still 100 metres, despite not being represented in this figure. By using time spreading, MPR-T achieves a larger coverage range. However, this leads to a loss of throughput due to requiring retransmissions. HDX systems also have a broader coverage with a reduced throughput, since they do not possess a downlink channel. A MT outside the FDX range may transmit to the AP using HDX concurrently with other transmissions as long as the energy received at the AP is within the accepted range defined above. On the other hand, when the AP transmits to these MTs, it must use HDX, as the transmission power bound defined for FDX listed in table 3.1 does not allow the MTs to correctly receive the AP's packets. Therefore, for a given FDX SIR, it is possible to define the FDX region represented in figure 3.6(a) for MPR-IC and MPR-T.

3.3.2.5 Multipacket reception performance with full-duplex

The plots in figure 3.11, illustrate the aggregated throughput for the FDX system with the MPR schemes considered. Figure 3.11(a) shows that the SPR FDX aggregated throughput is doubled within the FDX coverage range in relation to a HDX SPR system. When MPR-IC is used, figure 3.11(b) shows that the aggregated throughput is increased for a very short range (up to around 10 m for a SIR of 100dB). But for intermediate distances (between 10m and 55m for SIR of 100dB) the SPR FDX system provides the higher throughput. For farther distant MTs, figure 3.11(d) shows that MPR-T provides the higher aggregated throughput.

Figure 3.11(c) depicts the aggregated throughput for SPR-T where the number of MTs is lower than the spreading factor $S_{\mathrm{f}} = 2$, showing that SPR-T may suffer a performance degradation due to using a constant large spreading factor. In order to have the optimal performance, S_{f} must be equal to or lower than the number of MTs transmitting in the slot. These results show that the scheduling in the data channels should not only control the MT's transmission power and slots, but also define if FDX or HDX is used, select the MPR scheme and the S_{f} value (for MPR-T) in order to optimize the bandwidth and



(a) (b) (c) (d)

Figure 3.11: Aggregated throughput over distance. (a) SPR; (b) MPR-IC;(c) SPR-T; (d) MPR-T.

energy efficiency.

3.4 Medium access control protocol requirements

The results presented throughout this chapter can be used to extract a set of objective conditions that should be satisfied by the MAC protocol so that the system can operate in its optimal point. A single-hop cellular infrastructure system is considered. The set up selected should allow the AP and the MTs to reach the destination with a single transmission, in SPR scenarios. When many MTs try to send packets concurrently to the AP, the time redundancy may be used in order to successfully receive the packets.
In order to optimize the network capacity, the MAC protocol should be able to select the appropriate operation mode (FDX or HDX) depending on the packets in the AP and the MTs' queues while using the optimal transmission powers calculated throughout this chapter.
A FDX SIR of 80dB was considered since it is within the SIR achieved by all of the designs

covered in section 2.4. It is shown in table 3.1 that for a SIR of 80dB the maximum power that can be used is 52dBm. For this power level, it is shown in table 3.2 that the radius' of the zones are 10, 19 and 100 metres for the FDX, S-FDX and HDX zones respectively. The power levels used by the AP and the MTs are given by tables A.1 and A.2, described in section 3.3.1.2.

4

Full-duplex multipacket reception medium access control protocol

4.1 Introduction

This chapter presents the FM-MAC protocol. It starts by a small characterization of the protocol's design. After that, the simulation results are presented and validated with the theoretical expectations.

4.2 Protocol design

4.2.1 Objectives

The protocol was developed to achieve three main goals:

1. Have nodes take advantage of MPR's capabilities in order to increase throughput;

2. Have nodes engage in FDX communication whenever possible in order to increase throughput;

3. Allow nodes to switch between FDX and HDX transmission when channel's conditions are favourable for such interchange.

FM-MAC was inspired in two existing protocols: FD-MAC [SPS11] and H-NDMA [GPB-DOP13], already described in sections 2.5.1.1 and 2.7.4.2 respectively. The following sections describe the methodology behind the steps taken to comply with each objective and how H-NDMA and FD-MAC were modified in order to design a protocol that could fulfil the goals presented above.

4.2.2 Protocol characterization

Like in H-NDMA, FM-MAC uses a slotted data channel, where the AP is responsible for the coordination of the entire system. As described in section 3, each MT requires a unique ID attributed by the AP to each MT as soon as they join the network. This is called the association phase. After that, while the AP transmits in one slot, multiple MTs may also use that slot to transmit packets, as long as they respect the protocol. In order to use time diversity to resolve packet's collisions, the slots are organized into epochs. Figure 4.1 illustrates a simple packet exchange with FM-MAC.

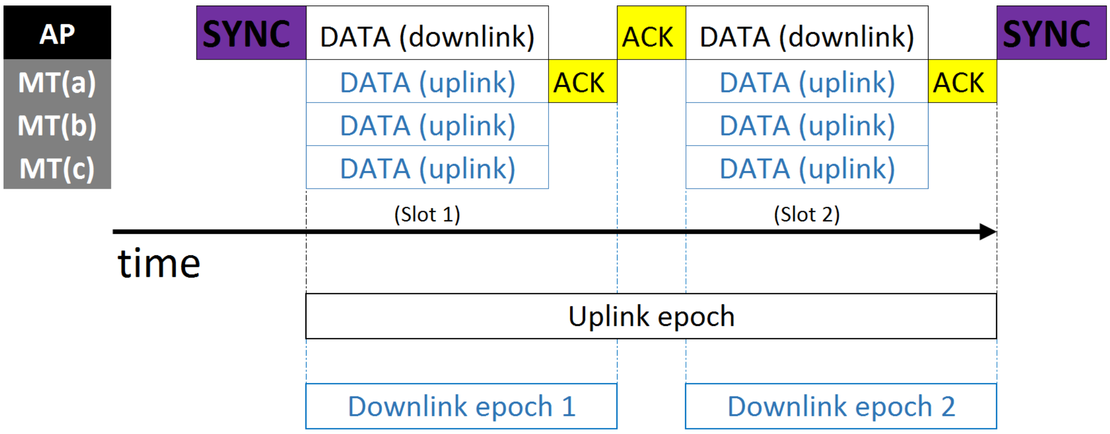


Figure 4.1: FM-MAC's packet exchange.

An epoch is defined as a set of slots used to transmit a set of packets. FM-MAC defines two types of epochs: the uplink epoch and the downlink epoch. The uplink epoch is used by a group of MTs to concurrently transmit packets. To signal the beginning of a new uplink epoch, the AP broadcasts a SYNC. This allows any MT with data packets to transmit in the next slot. MTs that do not transmit in the first epoch's slot are forbidden to send data until the next SYNC, i.e. the end of the epoch. Packets received with errors are retransmitted in the next slot within an epoch. The uplink epoch is terminated when all packets are received successfully by the AP or a maximum number of transmissions $max_{\text{TX}}^{\text{up}}$ is reached. The downlink epoch is used for the AP to transmit packets. The AP can signal the beginning of a new downlink epoch with one of two packets: a SYNC or an ACK. These packets signal the AP's destination that a packet is going to be sent to it in the next slot. The downlink epoch is terminated when the packet is received successfully by the MT or a maximum number of transmissions $max_{\text{TX}}^{\text{down}}$ is reached.
These two types of epochs are independent, therefore synchronization between the two is not necessary. As mentioned before, an uplink epoch is defined as the set of slots between two SYNCs where there is uplink transmission opportunity. On the other hand, a downlink epoch is bound to the beginning or ending with SYNCs, meaning an uplink

epoch can contain multiple downlink epochs. A FDX communication occurs when the two types of epochs overlap.
It is important to note that there is no need to distinguish between HDX and FDX communication from the MTs' transmission perspective. If a MT wishes to transmit, it can do so, regardless of its ability to be able to engage in a two-way simultaneous communication, as long as it has the AP's permission. The only requirement is that the MTs that want to transmit start to do so in the first slot of the uplink epoch. The protocol's mechanisms will become clearer in section 4.2.4.

4.2.3 Packet structure

This section describes the packets defined, their structure and the specific task they fulfil in the system.

4.2.3.1 Synchronization control packet

The SYNC is a packet broadcasted by the AP to signal the beginning and/or end of epochs (uplink and/or downlink). It also confirms the reception of the packets sent by the MTs during the previous epoch.

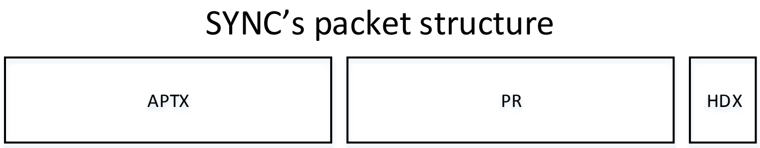


Figure 4.2: SYNC's packet structure

SYNC's fields are:

- Access Point Transmission (APTX): ID of the MT to which the AP is going to transmit during the epoch. If left blank it signals an Uplink Only (UO) epoch (explained in detail in section 4.2.4);
- Packets Received (PR): List of IDs of the MTs that were successful in their transmission during the last uplink epoch;
- Half-DupleX (HDX): One bit field to signal if the epoch is going to be strictly for a HDX downlink transmission.

4.2.3.2 Acknowledgement control packet

The ACK's main goal is to request packet retransmissions. Furthermore, it is used by the AP in order to delimit the downlink epochs.
The ACK's structure is represented in figure 4.3. AP's ReTransmission Needed (RTXN) and MT's RTXN are structurally equivalent and have the same main purpose: identifying the nodes that need to retransmit. However, their size and way they function has small,

but significant differences. Since the MTs only communicate with the AP, a one bit flag is suitable for this task. The AP, however, needs to send a list that contains the IDs of all the MTs that need to retransmit. Furthermore, since the downlink epoch's are independent as described before, AP's ACKs need to include the APTX field so that it can signal the beginning of a new downlink epoch.
MT's have an additional one bit field called Drop Packet (DP). It is used to force the AP to drop the packet it is trying to send.

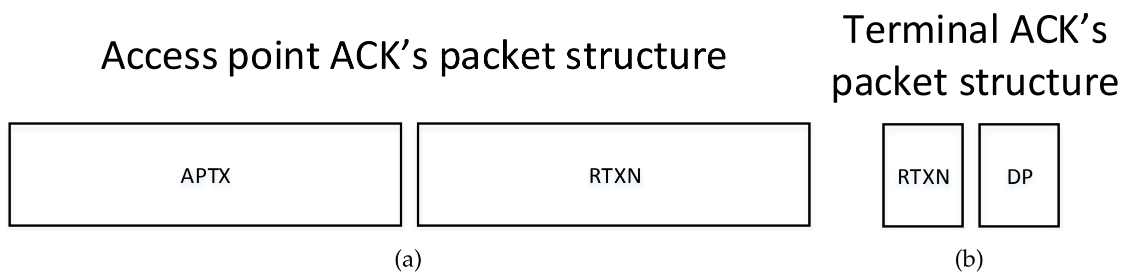


Figure 4.3: ACK's packet structure

4.2.3.3 DATA packets

DATA packets contain the information the nodes want to transmit and the Terminal Unique Orthogonal spreading-Sequence (TUOS). AP's TUOS needs to be unique and orthogonal for at least 2 hops, so that it can be used to resolve collisions using the H-NDMA receiver algorithm presented in chapter 3.

4.2.4 Operating modes

FM-MAC defines three types of operating modes. These are called Uplink Only (UO), Downlink Only (DO) and Uplink aNd Downlink (UND). All three are described in this section, covering the fundamental differences between them. It is important to note that the concept of epochs can be extended to the operating modes. Therefore, UO, DO and UND epochs are considered, which consist in the time interval between the SYNCs.
This analysis does not consider a maximum amount of transmissions or failed reception from physical layer headers so that the core aspects of the protocol can be covered in a clearer manner. Therefore, the use of the MT ACK's DP field is not described as this flag is only used for this specific task. An analysis on how the system reacts when it reaches the maximum number of transmissions or the reception of physical layer headers failures can be found in section 4.2.5.
In the figures of this section red DATA packets represent failed transmissions and green DATA packets represent successful transmissions. A value of 'X' means the field's value is not relevant for the specific task.

4.2.4.1 Uplink only mode

If the AP does not have any packets to transmit, the system mimics H-NDMA's behaviour, with a few tweaks in order to make it viable for continuous time access control. In UO mode only the MTs can transmit, meaning there will only be an uplink epoch. This allows the suppression of one of the ACKs, which decreases the overhead. An example of this procedure is shown in figure 4.4.

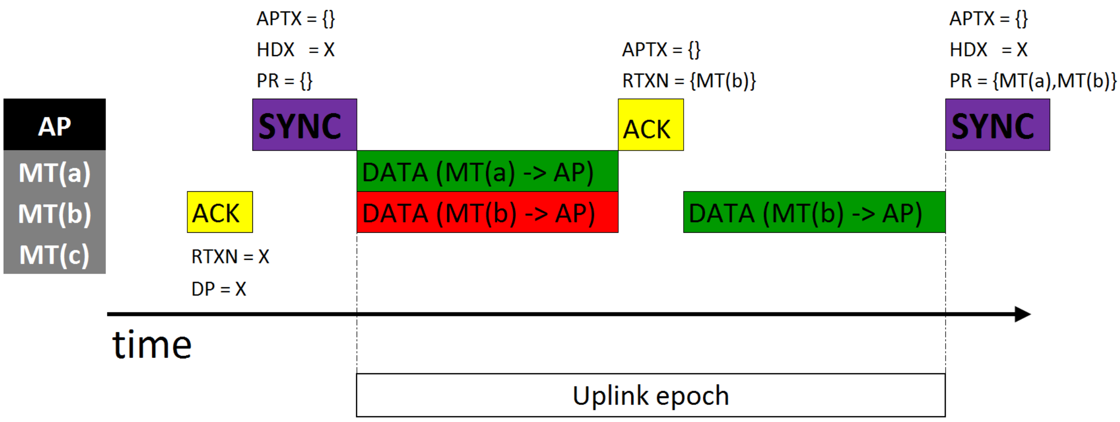


Figure 4.4: UO mode

In this example, MT(b) senses the transmission medium for a certain amount of time. Since the channel is idle, MT(b) expresses its intention to transmit by sending an ACK to the AP where its fields are unimportant. The AP immediately reacts to this by broadcasting a SYNC with *APTX = {}*. The SYNC signals the beginning of the uplink epoch and *APTX = {}* indicates that the AP does not wish to transmit during the uplink epoch. There was no epoch immediately before the one being considered, so the PR field is also empty. The AP will not be able to signal a downlink epoch until the current uplink epoch finishes. As soon as the SYNC finishes, any MT that has DATA packets to transmit starts to do so - in this case MT(a) and MT(b). The AP detects the collisions and requests for a retransmission of the unsuccessful packets by broadcasting an ACK packet with a list of the MTs that need to send the packet again. These MTs retransmit their packets and this is done until a maximum number of $max_{\mathrm{TX}}^{\mathrm{up}}$ transmissions is reached or all packets are received properly. In this example, all packets are received properly, so the AP broadcasts a new SYNC, in order to signal the beginning of the next uplink epoch with *PR = {MT(a),MT(b)}* to confirm the successful packet reception.

4.2.4.2 Downlink only mode

The DO operating mode is the least efficient as only one packet gets delivered during the epoch and is only used when the AP needs to reach a HDX MT. In this case, only the AP can transmit DATA and all MTs must wait for the next SYNC to transmit DATA. The system behaves a in similar fashion to H-NDMA, with the roles reversed. In DO mode, since only the AP can transmit, there will only be a downlink epoch. This allows the suppression of one of the ACKs, which decreases the overhead. An example of this procedure is shown in figure 4.5.

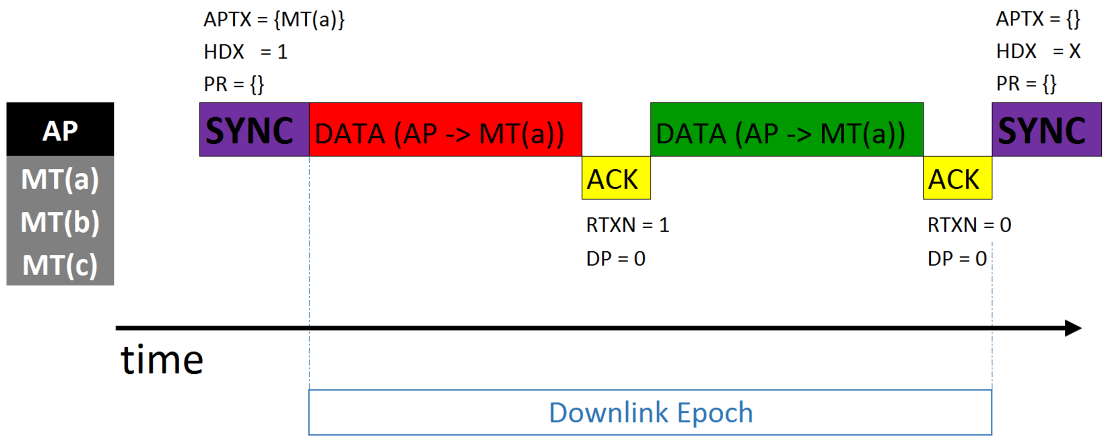


Figure 4.5: DO mode

In this example, the AP expresses its intention to transmit by sending a SYNC with *APTX = {MT(a)}* and *HDX = 1*. The SYNC signals the beginning of the epoch, *APTX = {MT(a)}* indicates the MT that the AP wishes to transmit to during the downlink epoch and *HDX = 1* expresses that it is a HDX communication. There was no epoch immediately before the one being considered, so the PR field is empty. As soon as the SYNC finishes, the AP starts to transmit DATA to its destination, in this case MT(a). If the transmission is not successful, the MT requests for an AP's retransmission of the unsuccessful packet by sending an ACK packet with *RTXN = 1*. The AP retransmits the packet until a maximum number of $max_{\mathrm{TX}}^{\mathrm{down}}$ transmissions is reached or the packet is received properly. In this example, the packet is received properly, so the AP broadcasts a new SYNC at the end to signal the beginning of the next epoch.

4.2.4.3 Uplink and downlink mode

The UND mode is the one that theoretically maximizes throughput by combining MPR with FDX communication. In UND mode, the system emulates a junction of the two operation modes described in the two previous sections. Therefore it uses a double ACK scheme like FD-MAC. There will always be a downlink epoch overlapping with an uplink epoch in the first slot. In this mode, the uplink epoch is the main epoch and the downlink is secondary. This means that the condition for a UND epoch to end depends solely on uplink packets being received properly.
An example of the UND mode procedure is shown in figure 4.6. In this example the AP expresses its intention to transmit by sending a SYNC with *APTX = {MT(a)}* and *HDX = 0*. It is assumed that either there was no epoch immediately before the one being considered, or no packets were transmitted, so the PR field is empty. The SYNC signals the beginning of the uplink epoch which (because it is the first slot of the UND epoch) matches the beginning of the downlink epoch. The field *APTX = {MT(a)}* indicates the MT

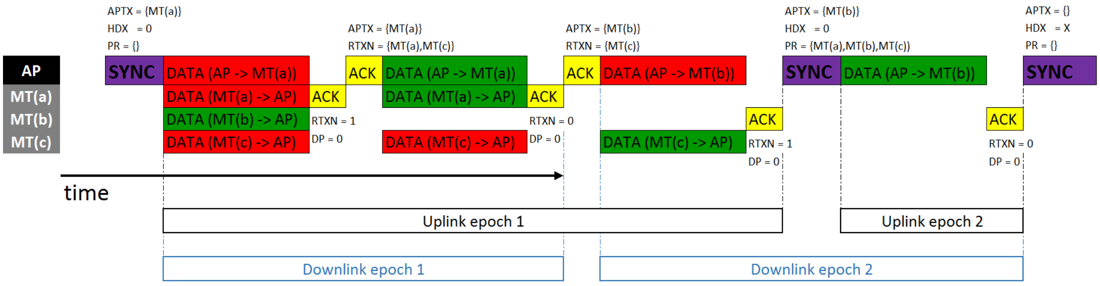


Figure 4.6: UND mode

that the AP wishes to transmit during the downlink epoch and *HDX = 0* expresses that it can be a FDX communication (if MTs have packets to be transmitted). As soon as the SYNC finishes, the AP and any MT that has DATA packets to transmit starts to do so. If the transmission from the AP is not successful, the MT requests for a retransmission of the unsuccessful packet by sending an ACK packet with *RTXN = 1*. The AP detects collisions and as soon as the MT's ACK finishes, it requests for a retransmission of the unsuccessful packets by broadcasting its own ACK packet with a list of the MTs that need to send the packet again. All the packets that failed to be received properly are retransmitted and this process is repeated until a maximum number of $max_{\text{TX}}^{\text{up}}$ transmissions is reached or all uplink packets are received properly. In this example, since the AP managed to reach its destination successfully in the second DATA slot, it was able to end the downlink epoch and start a new one, to send the next packet it has in queue. In the third slot, all the uplink packets are received properly, so the AP broadcasts a new SYNC, in order to signal the beginning of the next uplink epoch with *PR = {MT(a),MT(b),MT(c)}* to confirm the successful packet reception. In this case, the beginning of the uplink epoch does not match the beginning of the downlink epoch since the packet the AP was trying to send to MT(b) had still not been received properly. This process of having the AP retransmit its packet is repeated until a maximum of $max_{\text{TX}}^{\text{down}}$ transmissions is reached or the packet is received by the MT properly. As soon as it is, the MT sends an ACK packet with *RTXN = 0* which informs the AP the packet has been received successfully.

4.2.5 Maximum number of transmission reached and failed reception of physical layer headers

When a packet has been retransmitted $max_{\text{TX}}^{\text{up}}$ times for uplink or $max_{\text{TX}}^{\text{down}}$ times for downlink, the epoch that it is a part of is ended and the packet is dropped. An example of this mechanism in which $max_{\text{TX}}^{\text{up}} = max_{\text{TX}}^{\text{down}} = 2$ is shown in figures 4.7 and 4.8. Figure 4.7 illustrates a case where the AP's packet isn't received in $max_{\text{TX}}^{\text{down}}$ transmissions, where MT(a) sends an ACK with *PD = 1*. This forces the AP to drop the packet and proceed with the next iteration of its algorithm. It is also important to note that a SYNC is sent, even though the AP's packet has not been received properly. This happens because the uplink epoch is always the main epoch and is the one that dictates when the

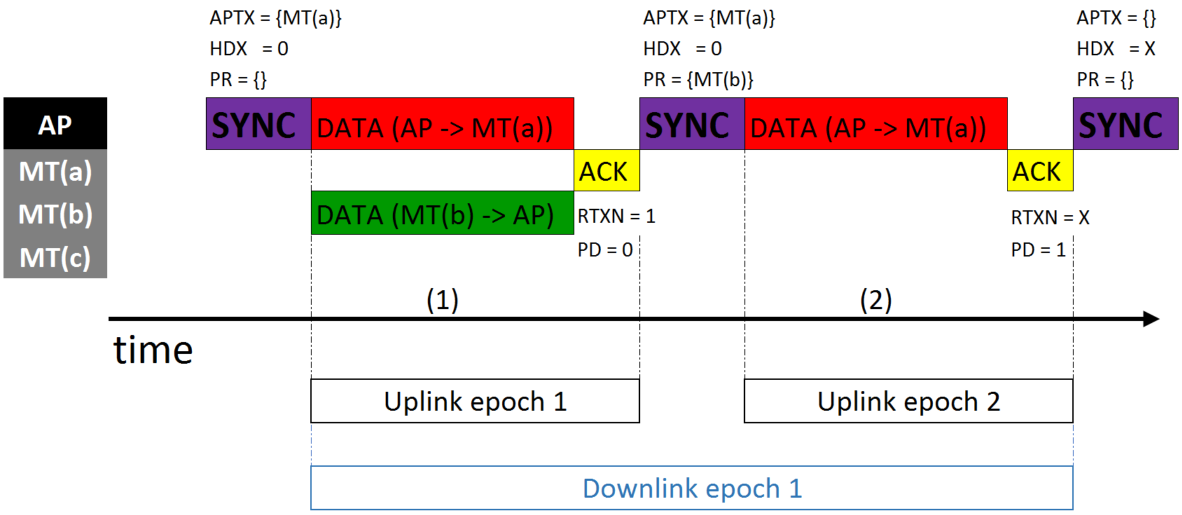


Figure 4.7: AP forced to dropped packet.

UND epoch finishes.

If a given MT is not able to successfully receive the physical preamble, it may not separate the desired signals at the reception due to the added noise caused by the unresolved MTs' signals. In these cases, MPR techniques may fail and the MT does not broadcast an ACK. This results in the AP waiting the full duration of the ACK and then continuing with the protocol's order of events, as if a retransmission was being requested. Even though the MT did not try to resolve the packet, this still counts as a transmission.

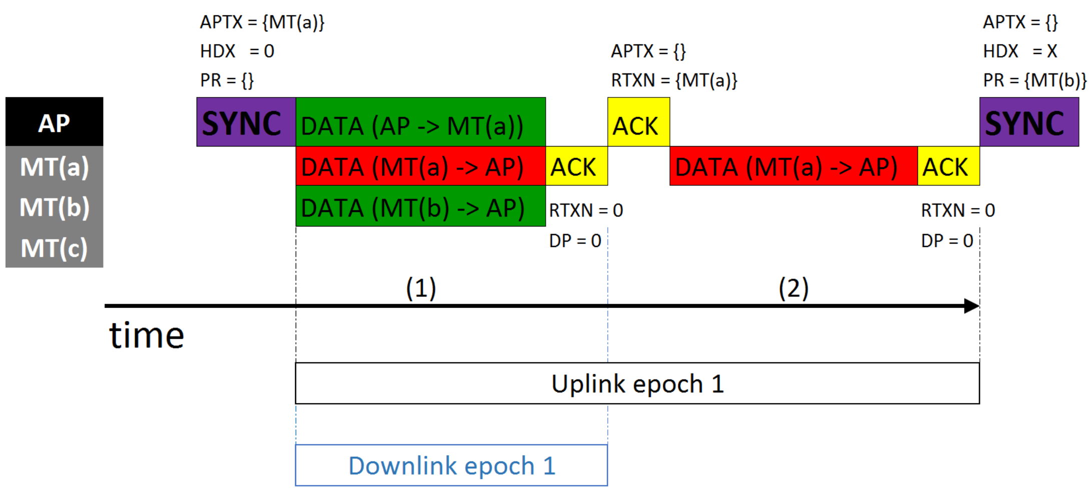


Figure 4.8: MT forced to dropped packet.

Figure 4.8 illustrates a case where MT(a)'s packet is not received in $max_{\mathrm{TX}}^{\mathrm{up}}$, where the AP sends a SYNC packet with *PR = {MT(b)}*, excluding MT(a) from this list. This forces the MT to discard its packet. The PR list serves not only as a way to force packets to drop a packet, but also as a way for all MTs to confirm the successful reception of their packets. This is particularly important in case the AP happens not to be able to decode a MT's

TUOS properly. When this happens, the AP is not able to request a retransmission since it doesn't know the TUOS of the MT that it failed to receive the packet. This way, the MT does not transmit until the end of the epoch. The MT only tries to send the packet again when the epoch ends, since its TUOS was not in the PR list.

4.2.6 Power control

As described in chapter 3, power control is important in order to assure that the multiple concurrent packets can be resolved properly. This section describes how the power levels determined in section 3.4 are adopted in the MAC protocol. To put it simply, a node transmits with the power levels given by the HDX Table A.1 when its destination is not transmitting itself. Otherwise, it transmits with the power levels given by the FDX Table A.2. As described in section 3.4, these are the lowest levels of power that guarantee successful receptions with an error probability of 1% for both cases.
In order for the AP and the MTs to determine the distance between each other, a periodic beacon with a fixed power level is broadcasted by the AP. The MTs use the power level received at their interface to estimate the distance between their location and the AP's. This distance is stored by each MT and reported back to the AP. After receiving this control packet from every MT, the AP improves the distance estimation to each of the MTs by measuring the received power and stores the information. After this short packet exchange, each MT uses the distance measured to look up in tables A.1 and A.2 described in section 3.3.1.2 for the $P^{p}_{\mathrm{t}_{HDX}}$ and $P^{p}_{\mathrm{t}_{FDX}}$. The AP does the same for each MT, constructing a table of $P^{AP_p}_{\mathrm{t}_{HDX}}$ and $P^{AP_p}_{\mathrm{t}_{FDX}}$.
In UO and DO modes, the power levels used by both the AP and the MTs are always $P^{p}_{\mathrm{t}_{HDX}}$ for the MTs and $P^{AP_p}_{\mathrm{t}_{HDX}}$ for the AP, since both these modes only employ one-way communication. In FDX however, there are a few different possible outcomes, which means that the power levels require micro management in order to both ensure packet resolution and use the least amount of power. Next section covers how the power levels adapt from the MT and the AP's perspective.

4.2.6.1 Uplink and downlink mode from the mobile terminal's perspective

During a UND epoch, the MT is always able to identify if the AP is transmitting or not, by checking the APTX field of the SYNCs and ACKs broadcasted by the AP. According to that information it decides to use the power levels given by $P^{p}_{\mathrm{t}_{HDX}}$, or the power levels given by $P^{p}_{\mathrm{t}_{FDX}}$. As covered in chapter 3, the MTs are able to choose between a SPR resolution or a MPR resolution. Resolving the AP's packet by MPR is more computationally complex as it requires the MT to resolve all packets being sent with the MPR technique, select the one that has the AP as a source and discard the rest. If the packet's resolution is performed with SPR, the content received from the rest of the MTs is considered part of the channel's noise and only the packet the MT wants to receive is addressed. Preferably, MTs should use SPR, but this may be impossible in high density scenarios or if other MTs are transmitting at close quarters, as the interference generated by these transmissions is too high. Therefore, MTs perform concurrent reception using both SPR and MPR. They use the one that first correctly receives the packet.

4.2.6.2 Uplink and downlink mode from the access point's perspective

Unlike the case just described, the AP is not at all times aware if its destination is transmitting or not. A soon as the SYNC broadcasted by the AP finishes, any MT is free to transmit if it has packets in its queue. This means that the AP is unable to identify if its destination is transmitting or not in the first slot of the UND epoch. This means that in the first slot of the UND epoch the AP is not able to: (i) optimize the power level for its transmissions and (ii) identify S-FDX MTs. This could be solved with one of two different approaches:

1. Forcing the AP's destination to announce to the AP if it intends to transmit in the upcoming epoch or not, before any transmission;

2. Allowing the AP to forbid a MT from transmitting in the upcoming epoch.

The first method could have been easily implemented, but it would have further increased the overhead at the beginning of a UND epoch.
The second method does not increase the overhead, but makes for a much more complex system and can potentially delay uplink packets. In order to avoid this, a one bit field can be added to the DATA packets transmitted by each MT, informing the AP if the MT has more packets in queue. This allows the AP to have a better perspective of which MTs it should and should not forbid from transmitting, but can still cause delays if a packet enters a given MT's queue during a period where it is not able to inform the AP. Statistical methods could also be used, to estimate the probability of a MT transmitting, with increased complexity. However, given the relative low gain that could be expected and the fact that no S-FDX MTs were considered for the performance analysis, we decided to implement a conservative approach in FM-MAC protocol.
The AP always assumes its destination is transmitting in the first slot of the uplink epoch. By doing so, in the first slot of the uplink epoch, the AP always transmits with the power levels $P^{AP_p}_{\mathrm{t}_{FDX}}$. It then adapts its power level for the remaining slots of the uplink epoch. This is possible since as soon as the MTs finishes transmitting in a given DATA slot, the AP is able to detect which packets are no longer required to be retransmitted. If the AP's destination does not require further retransmissions or did not transmit in the first slot, the AP uses the power level of $P^{AP_p}_{\mathrm{t}_{HDX}}$. This power adaptation allows the AP to use an optimal power level for the specific MT it is trying to reach. However, this can lead to reception problems by the MT in high density scenarios. For this reason, the exclusive SYNC mechanism was created.

4.2.7 Inter-terminal interference and the exclusion synchronization control packet

Even though MPR's main goal is to address ITI generated by adjacent MTs, having multiple MTs transmitting at close quarters might hinder the AP's destination from correctly receiving a packet. This forces the AP to retransmit numerous times, which reduces the downlink's throughput. This can be optimized by exploiting the AP's beamforming capabilities to transmit a SYNC to a specific area, excluding the nodes in the neighbourhood of the destination to transmit. This would allow the AP to prevent uplink transmissions of certain MTs in order to lessen ITI of the MT it is trying to reach.

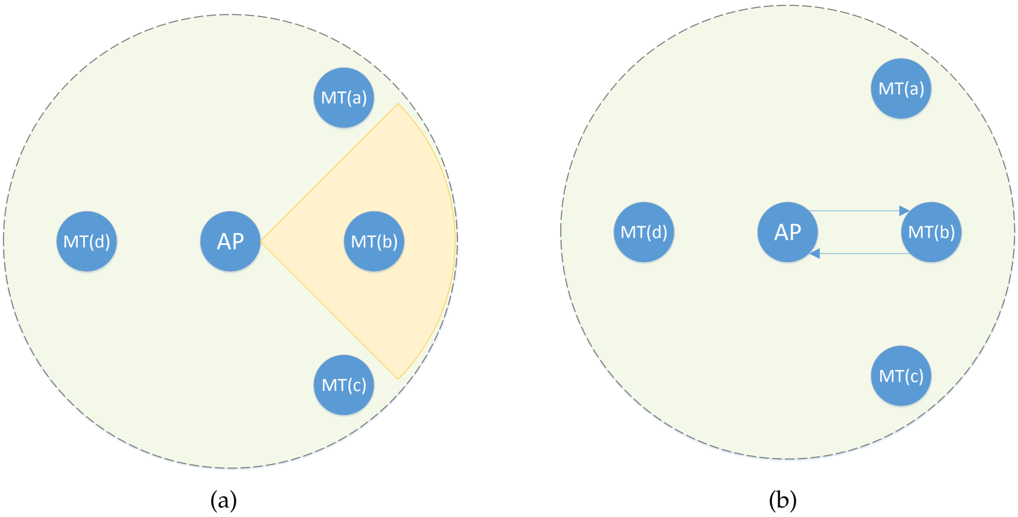


Figure 4.9: (a) exclusive SYNC; (b) exclusive packet exchange between the AP and MT(b).

Figure 4.9(a) shows the AP transmitting an exclusive SYNC to MT(b). Since MT(a), MT(c) and MT(d) did not receive the SYNC, only MT(b) is able to exchange packets with the AP (figure 4.9(b)).

4.2.8 Maximizing full-duplex communications and fairness control

Like FD-MAC, FM-MAC uses a mechanism to maximize FDX communications. This mechanism involves delaying packets that need to be sent to HDX terminals, and pass over packets which may be transmitted using FDX. Such a mechanism is helpful, but it is important to impose some kind of fairness control so that the FDX MTs are not always favoured as that would lead to an usurpation of the channel by their part.
The AP is the one that decides the type of epoch that is going to be used. This decision started by being made by using a First In First Out (FIFO) approach, as illustrated by algorithm 1.
The problem with this procedure is that the DO mode ceases uplink transmissions. This means that if there are a lot of packets for HDX MTs in the AP's queue, it will block uplink transmission until it reaches a packet to a FDX MT or the AP empties its queue.

Algorithm 1 FIFO approach.

```
if first packet in queue is for FDX MT then
    operating mode = UND mode;
else if first packet in queue is for HDX MT then
    operating mode = DO mode;
else
    operating mode = UO mode;
end if
```

To resolve this issue an algorithm that moved FDX packets to the beginning of the queue was initially implemented.

However, with this new algorithm, FDX communications are always preferred over HDX ones, which led to a problem: as long as there are packets for FDX MTs in the AP's queue, these would always move to the beginning of the queue, causing the packets for the HDX MTs to be delayed constantly. To solve this, an algorithm is proposed to determine the amount of packets that could be moved to the beginning of the queue in a fair manner.

The algorithm proposed in this dissertation is based in a credit system to either allow HDX transmissions or have a FDX packet moved to the beginning of the queue. The AP possesses a variable called $Downlink_{\text{credits}}$ which denotes the amount of slots that can be used in DO mode and balances the amount of uplink and downlink slots. Whenever the main epoch has uplink capability (which happens in UO and UND mode), the number of slots used in that main epoch are added to $Downlink_{\text{credits}}$. If the epoch does not have uplink capability (which happens when the operating mode is HDX), the number of slots used in that epoch are subtracted from $Downlink_{\text{credits}}$.

With this mechanism, the AP can only signal a DO epoch if it has at least one credit available (which is normally enough for the AP to reach the MT in DO mode). If it does not have at least one credit, the AP is forced to signal an uplink epoch, in order to earn credits that allow it to transmit in DO mode. If the AP has a packet that needs to be transmitted to a FDX MT in its queue, it moves it to the beginning of the queue, and signals a UND epoch. If not, the AP signals a UO epoch (even if no MTs happen to want to transmit).

In addition to $Downlink_{\text{credits}}$, a second variable called Max_{credits} was added to prevent the AP from having too many credits, so that it cannot signal a sizeable burst of DO epochs. It also makes sure that there are not too many FDX packets being favoured. As soon as $Downlink_{\text{credits}}$ reaches Max_{credits}, it cannot increase any higher and no additional FDX packets can be moved to the beginning of the queue. Despite this, the AP will continue to signal UND epochs if the packets in the beginning of the queue are for FDX MTs. Max_{credits} is calculated using

$$Max_{\text{credits}} = \left\lceil max_{\text{TX}}^{\text{down}} \frac{HDX_{\text{MTs}}}{Total_{\text{MTs}}} \right\rceil, \tag{4.1}$$

where $\lceil x \rceil$ denotes the ceiling operation, which returns the smallest integer equal to or above x. This way, the amount of maximum DO epochs in a row are proportional to the amount of HDX MTs in the system. The pseudo code can be written as in algorithm 2.

Algorithm 2 Final operating mode selector.

```
for each slot until epoch finishes do
    if slot had uplink capability then
        Downlink_credits = Downlink_credits + 1
    else
        Downlink_credits = Downlink_credits − 1
    end if
end for

if Downlink_credits >= Max_credits then
    Downlink_credits = Max_credits
end if
if first packet in queue is for HDX and Downlink_credits < 1 then
    for each packet in queue do
        if packet is for a FDX MT then
            move FDX packet to the beginning of the queue;
            break cycle;
        end if
    end for
    if first packet in queue is for FDX MT then
        operating mode = UND mode;
    else
        operating mode = UO mode;
    end if
else
    if first packet in queue is for FDX MT then
        operating mode = UND mode;
    else if first packet in queue is for HDX MT then
        operating mode = DO mode;
    else
        operating mode = UO mode;
    end if
end if
```

The same concept applies when the AP finishes one transmission and wants to commute to a different FDX or S-FDX MT during an UND epoch. When the AP has yet to resolve all MTs' packets and successfully transmits a packet to a MT, it attempts a new FDX transmission. If the first packet in the AP's queue is for a FDX or S-FDX MT, the AP starts transmitting. If not, it checks if $Downlink_{\text{credits}}! = Max_{\text{credits}}$ in order to know if it can move a FDX or S-FDX to the beginning of the queue. If it can, it looks in the whole queue for a packet for a FDX or S-FDX MT and moves it to the beginning. The pseudo code for this mechanism is depicted in algorithm 3.

Algorithm 3 AP commutes transmission (during UND epoch).

```
if first packet in queue is for FDX or S-FDX MT then
    start transmitting;
    return;
end if

if Downlink_credits != Max_credits then
    for each packet in queue do
        if packet is for a FDX MT or S-FDX MT then
            move FDX packet to the beginning of the queue;
            start transmitting;
            return;
        end if
    end for
end if
```

4.3 Simulation results

4.3.1 Simulation scenario

This section presents a set of simulation performance results for the system composed by the MPR/SPR receiver presented in chapter 3, controlled by FM-MAC described throughout chapter 4. As in the simulations ran in section 3.3, a SC-FDE modulation is considered with an FFT-block of N = 256 data symbols, a cyclic prefix of 32 symbols, longer than the overall delay spread of the channel, using a bandwidth of 64 MHz. FDX SIR was fixed at 80dB. Association phase, periodic beacons and their response were not considered for simulation purposes. The exclusive SYNC mechanism was not implemented in the simulator. Packets' duration was normalized for a DATA packet and are depicted in table 4.1.

Type of packet	Duration
DATA	1
ACK	$\frac{1}{10}$
SYNC	$\frac{1}{20}$

Table 4.1: Packets' duration.

Two types of scenarios were considered: with 3 and 10 MTs. The distances were set at 5 metres for FDX MTs and 30 meters for HDX MT (no potential S-FDX MTs were considered). They were separated in a equiangular style as illustrated in figure 4.10.
The FDX MTs' are distributed as far apart from each other as possible, to reduce the ITI. This decision was made given that the interface management strategy proposed based on directional SYNCs was not implemented. Therefore, the set up was defined to avoid its

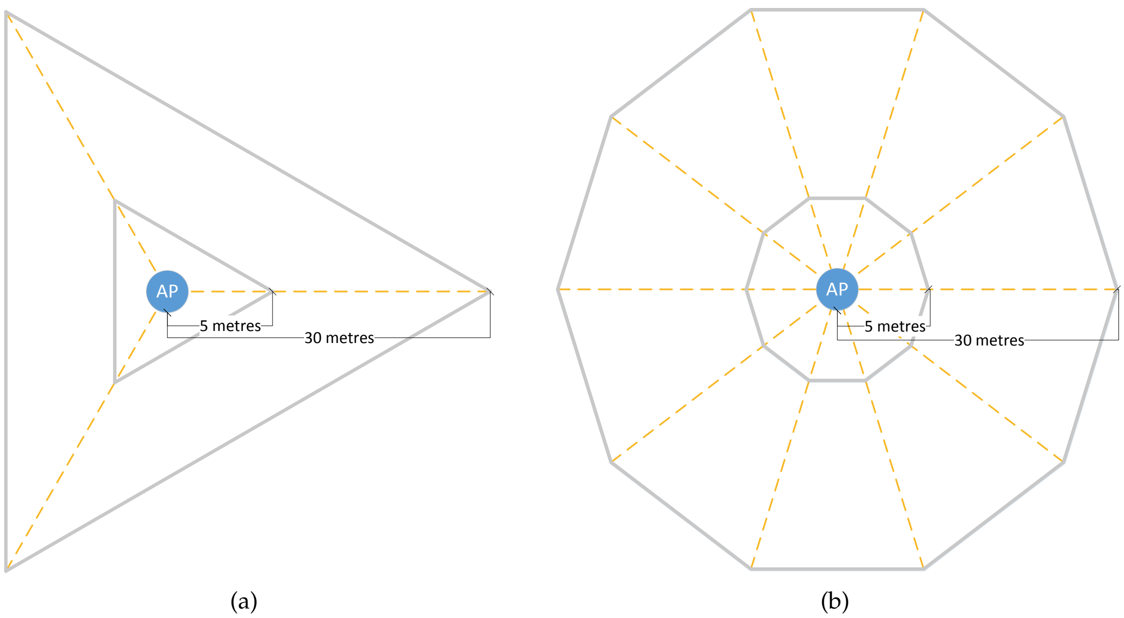


Figure 4.10: MTs' distribution. (a) 3 MT scenario; (b) 10 MT scenario.

use, especially for FDX MTs that employ MPR resolution techniques that receive a higher power from an adjacent HDX MT compared to an adjacent FDX MT. Naturally, this strategy only matters for the 10 MTs scenario, since with 3 MTs they are all equidistant from each other. Table 4.2 depicts the distances used for each MT with 10 MTs.

Scenario	Distance (metres)									
	MT(a)	MT(b)	MT(c)	MT(d)	MT(e)	MT(f)	MT(g)	MT(h)	MT(i)	MT(j)
10FDX - 0HDX	5	5	5	5	5	5	5	5	5	5
9FDX - 1HDX	5	5	5	5	5	5	5	5	5	30
8FDX - 2HDX	30	5	5	5	5	30	5	5	5	5
7FDX - 3HDX	5	5	5	30	5	5	5	30	5	30
6FDX - 4HDX	5	5	30	5	5	30	5	5	30	30
5FDX - 5HDX	5	30	5	30	5	30	5	30	5	30
4FDX - 6HDX	30	5	30	30	5	30	5	30	30	5
3FDX - 7HDX	5	30	30	5	30	30	30	5	30	30
2FDX - 8HDX	5	30	30	30	30	5	30	30	30	30
1FDX - 9HDX	5	30	30	30	30	30	30	30	30	30
0FDX - 10HDX	30	30	30	30	30	30	30	30	30	30

Table 4.2: MT's distribution per scenario.

The maximum number of retransmissions was set based in the measurements presented in table 3.3(b) ($max_{\mathrm{TX}}^{\mathrm{up}} = max_{\mathrm{TX}}^{\mathrm{down}} = 3$ for the 3 MT scenario and $max_{\mathrm{TX}}^{\mathrm{up}} = max_{\mathrm{TX}}^{\mathrm{down}} = 7$ for the 10 MT scenario).

The load of the AP and each MT was determined by a Poisson distribution with a mean λ_{AP} for the AP and a mean λ_{MT} common for all MTs. Therefore, the aggregate uplink load can be calculated using

$$load_{\text{uplink}}^{\text{aggregate}} = Total_{\text{MTs}} \times \lambda_{\text{MT}}. \tag{4.2}$$

The destinations for the AP's packets were randomly generated with equal probability for all MTs. The simulations ran had a maximum time of 5000 time units, where the first and last 500 time units were discarded in order to allow the system to stabilize and ignore the queuing effect respectively.
To analyse the system's response to several aggregated uplink loads, the 10 MT scenario was characterized by a set of 20 simulations for *10FDX - 0HDX*, *5FDX - 5HDX* and *0FDX - 10HDX*. These simulations had a fixed downlink load of 50% and a variable aggregate uplink load from 0% to 200%.

4.3.2 Average number of transmissions

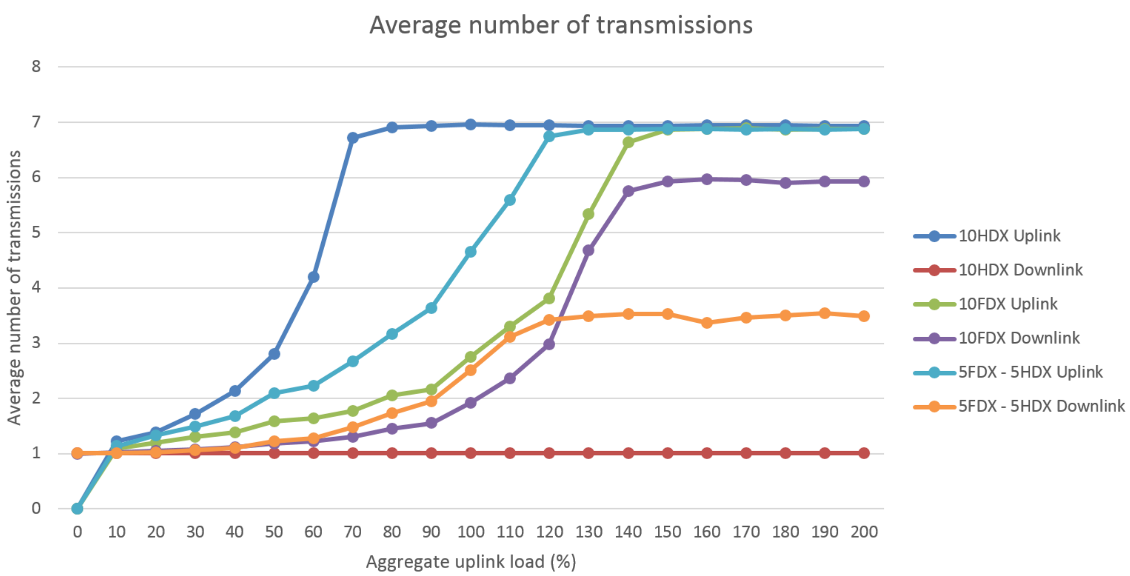


Figure 4.11: Average number of transmissions.

Figure 4.11 depicts the average number of transmissions required for a successful packet reception. It shows that higher uplink loads results in having more MTs transmitting concurrently and in the limit, makes the AP require 7 transmissions to successfully receive all packets. For the *0FDX - 10HDX* scenario, 1 transmission is usually enough for the AP to reach its destination since the AP is the only one accessing the channel. However, this delays the MT's packets more than its FDX alternatives, which makes the system converge to a saturated system where all MTs are transmitting concurrently with lower uplink loads.
The *10FDX - 0HDX* scenario is the one where the AP requires the highest number of transmissions in order to successfully reach its destination. This happens because all MTs are accessing the channel concurrently and the ITI generated increases the difficulty

of the reception, requiring the use of MPR most of the time.
The number of transmissions for the uplink follow the pattern by tables 3.3(a) and 3.3(b) described in section 3.3.2.1. The downlink's transmissions saturate at lower levels since the ITI generated by the MTs that are the most distant from the AP's destination are negligible due to the attenuation.

4.3.3 Queuing delay

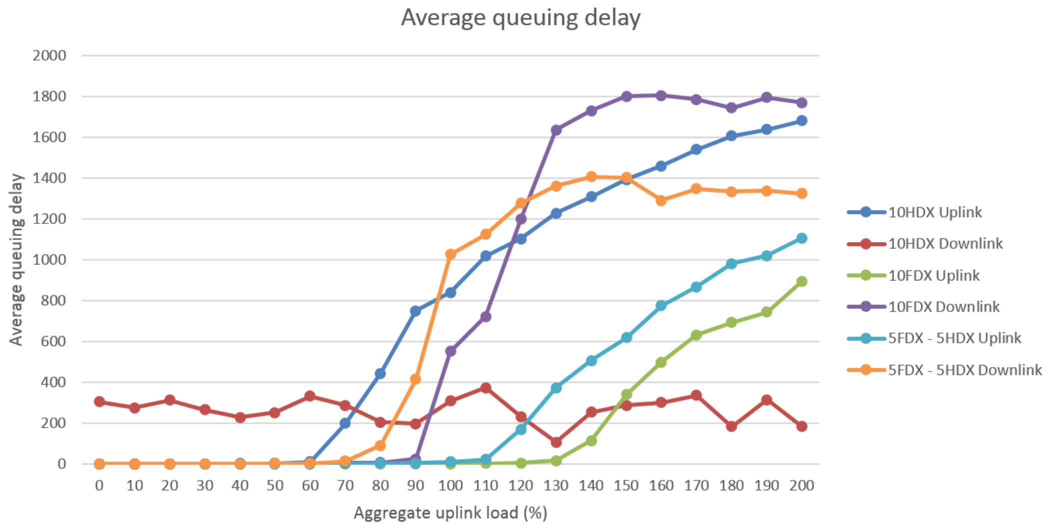


Figure 4.12: Average queuing delay

Figure 4.12 depicts the system's average queuing delay, for the scenarios considered. The AP's delay for the *0FDX - 10HDX* scenario does not depend on the amount of aggregate uplink load as the fairness control mechanism forces the system to have a 50% uplink and 50% downlink distribution in this scenario. This means that only the number of slots that are attributed to each type of transmission in a short burst differ. If the MTs do not have anything to transmit, the AP forces an uplink slot followed by a downlink slot. If the system is saturated, a periodic behaviour appears with 7 slots attributed to uplink followed by 7 slots for downlink.
As expected, replacing HDX MTs with FDX MTs leads to lower queueing delays for uplink transmissions, regardless of scenario or aggregated uplink load considered. On the other hand, for downlink transmissions, the *0FDX - 10HDX* scenario is the most stable, though not the one with the lowest delays. With the replacement of HDX MTs with FDX ones, the system tends to delay downlink transmissions due to the increasing time wasted with AP retransmissions. This suggests that the considered system requires a mechanism that statistically estimates the load of each MT in the system. If the aggregate uplink load goes above a certain threshold, the AP could force the system to work in a HDX fashion.

4.3.4 Energy efficiency

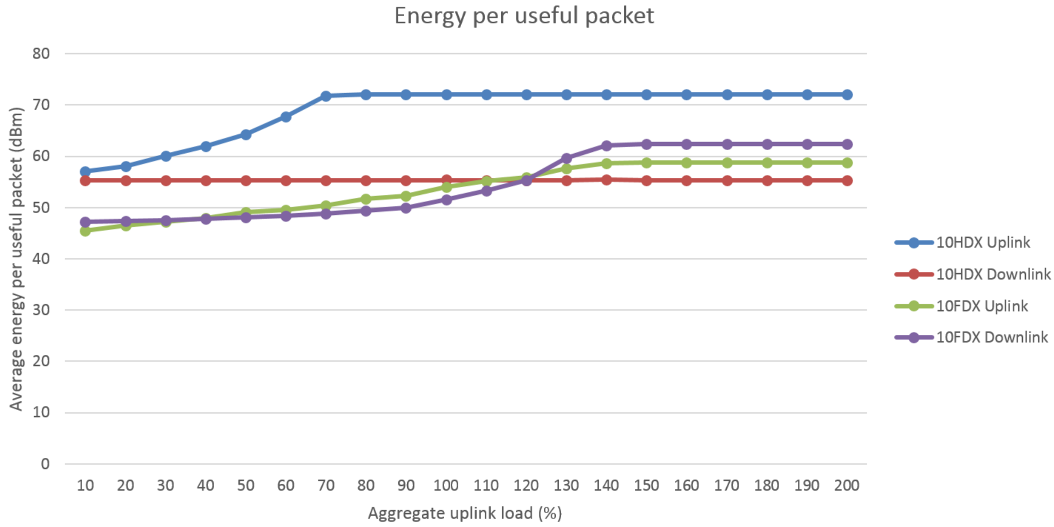


Figure 4.13: Average EPUP for the *10FDX - 0HDX* and *0FDX - 10HDX* scenarios.

Figure 4.13 depicts the average EPUP for the *10FDX - 0HDX* and *0FDX - 10HDX* scenarios. Since HDX MTs are farther away from the AP, comparing their uplink or downlink absolute power levels is an unfair comparison. However, the power fluctuation shows that the uplink EPUP for the *0FDX - 10HDX* scenario tends to saturate much quicker (around 70% aggregate uplink load) than its FDX alternative (which reaches full saturation at 140%). This happens because uplink packets in HDX are much more delayed than their FDX alternative, which makes the HDX system tend towards a scenario where all MTs are concurrently transmitting with lower aggregate uplink loads. When all MTs are transmitting concurrently at all times, 7 transmissions are required for all packets to be resolved, which in turn makes the EPUP rise.

For the downlink EPUP, since one transmission is usually enough for HDX, the AP is able to maintain a stable EPUP of 55 dBm (transmission power for the AP to reach the HDX MTs at 30 metres). For FDX the downlink EPUP tends to be higher than the HDX's, despite using inferior power. This happens because in high density scenarios, 6 transmissions are required for the MT to be able to successfully receive the packet the AP is transmitting. This translates into more transmissions being required, which in turn makes the EPUP rise.

Figure 4.14 depicts the average EPUP for the *5FDX - 5HDX* scenario. Intuitively, since half of the packets delivered by the AP are for HDX MTs, it would be expected that the AP's EPUP was in-between the HDX and FDX's EPUP for all aggregate uplink loads. However, this is only the case for low load scenarios (from 10 to around 30% aggregate uplink load). For higher load scenarios EPUP stabilizes at around 1 dBm higher than the FDX's EPUP. This happens because in a high density scenarios, 6 transmissions are required for each downlink packet to be successfully received by a FDX MT while only 1 transmission is required for HDX MTs. This way, the power level used for FDX MTs with

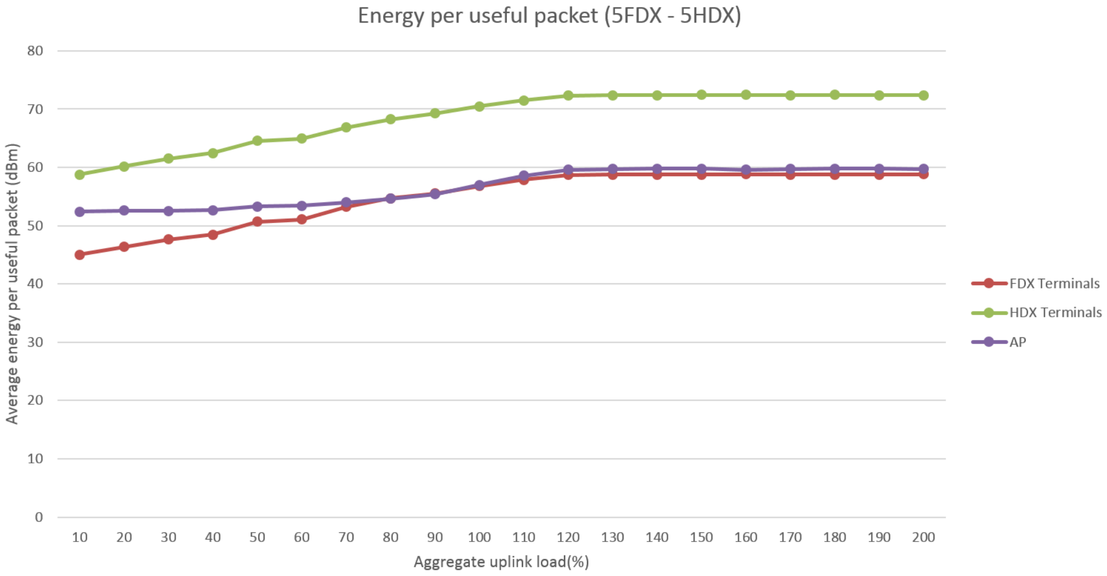


Figure 4.14: Average EPUP for the *5FDX - 5HDX* scenario.

high uplink loads is 6 times the power level used for FDX MTs with low uplink loads, which results in only a small increase of the downlink's EPUP (instead of rising to the middle of the uplink's EPUP).

4.3.5 Multipacket reception at the terminal

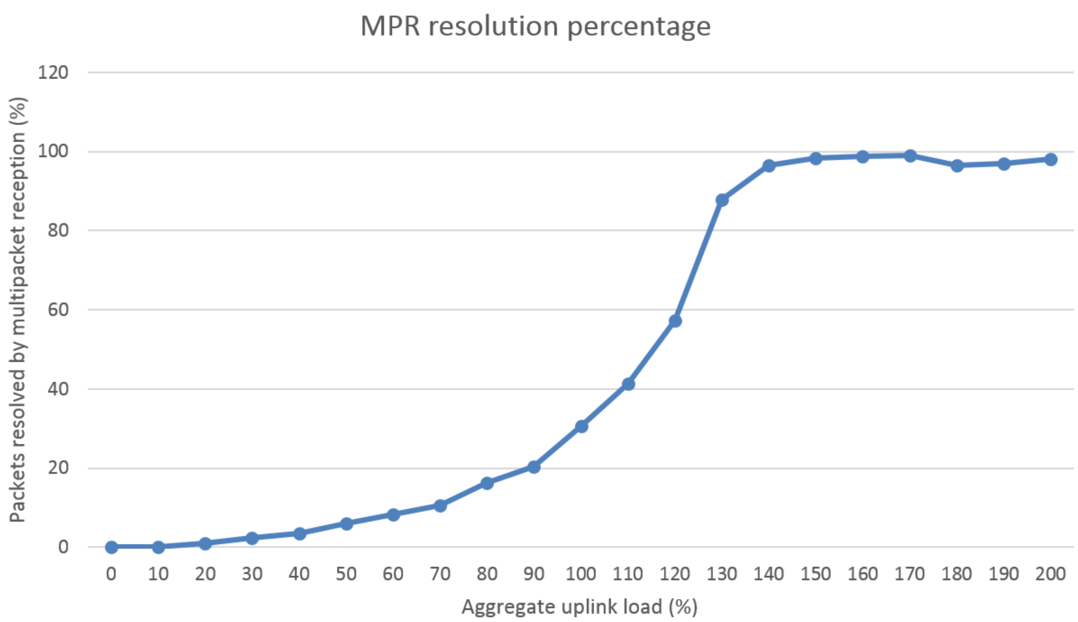


Figure 4.15: MPR resolution percentage for the *10FDX - 0HDX*

Figure 4.15 shows the percentage of packets resolved by MPR, over the aggregate uplink load. Resolving a packet by SPR is only possible when the interference levels are low, which translates to low density scenarios and when the MT that is receiving the packet is far away from MTs transmitting packets. This is more likely to happen with low uplink loads. On the other hand, high aggregate loads lead to a high transmission density, making the channel's interference too high for the AP's destination to be able to resolve the packets by SPR. When this happens, MPR converges to a successful reception faster than SPR.

4.3.6 Throughput

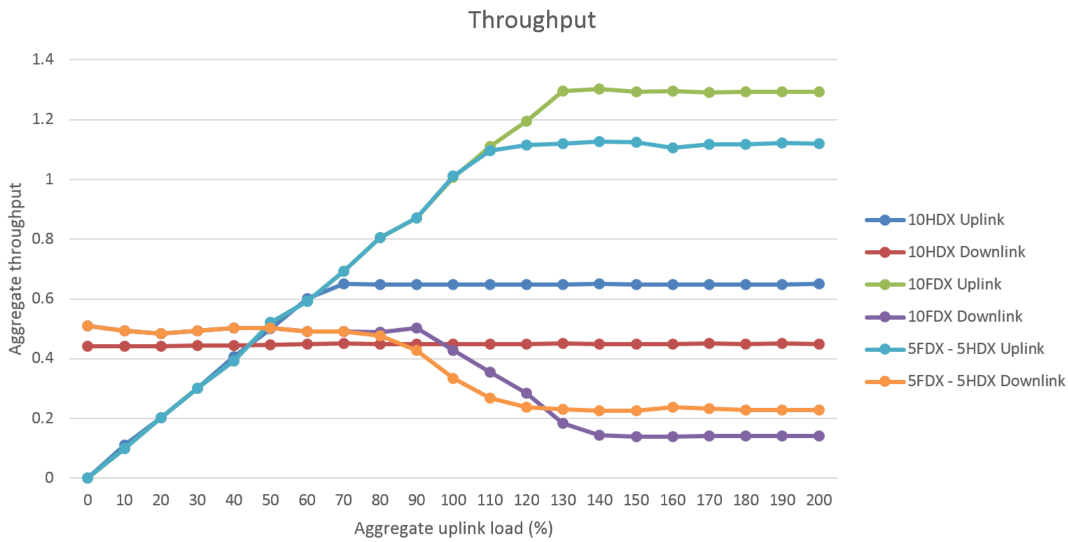


Figure 4.16: Downlink and aggregate uplink's throughput

Figure 4.16 depicts the throughput increase achievable by replacing HDX MTs by FDX MTs. As with the delay, in a HDX scenario the fairness system forces the system to have a 50% uplink and 50% downlink distribution, which allows the *0FDX - 10HDX* scenario to maintain its downlink throughput, regardless of the aggregate uplink load considered, but causes the aggregate uplink throughput to max out at 0.65.

10FDX - 0HDX and *5FDX - 5HDX* scenarios suggest that replacing HDX MTs with FDX MTs will always lead to a higher aggregate uplink throughput. However, in scenarios with high uplink load, the downlink throughput decreases. Figure 4.17 shows that even though the downlink throughput drops with the replacement of HDX MTs by FDX MTs, the system still achieves higher total aggregate throughput (downlink + aggregate uplink).

To characterize the system's response to a saturated system, the 3 and 10 MT scenarios were fixed with a downlink load of 90% and an aggregated uplink load of 270% and 900% respectively.

Figure 4.18 depicts the saturation throughput gain achieved by having MTs engage in FDX communications. It shows that 3 FDX MTs manage to deliver 2.34 times more packets than its HDX alternative. As for downlink, the AP only manages to increase

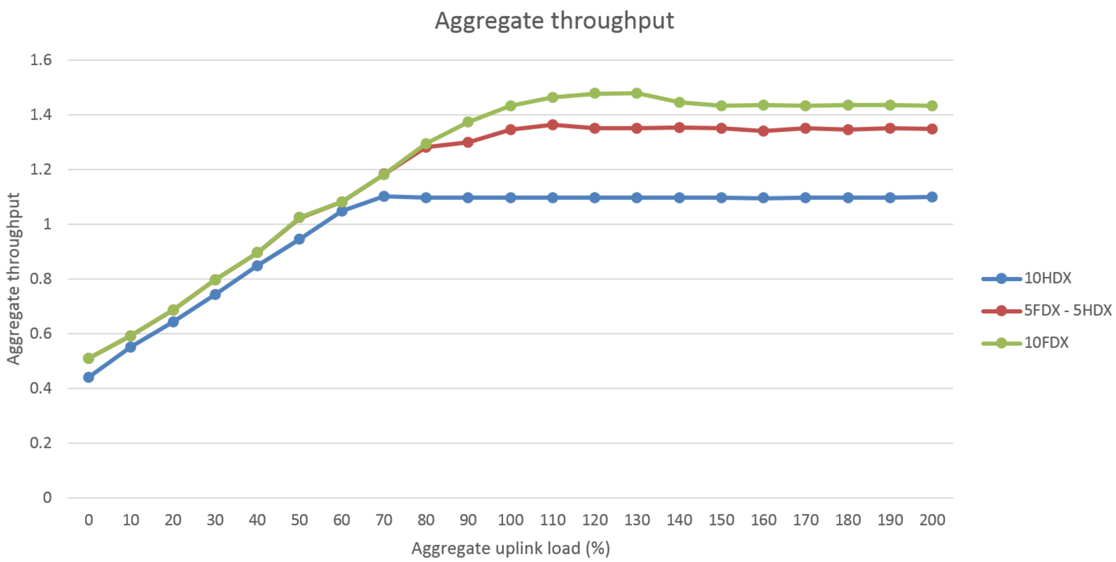


Figure 4.17: Aggregate throughput (uplink + downlink)

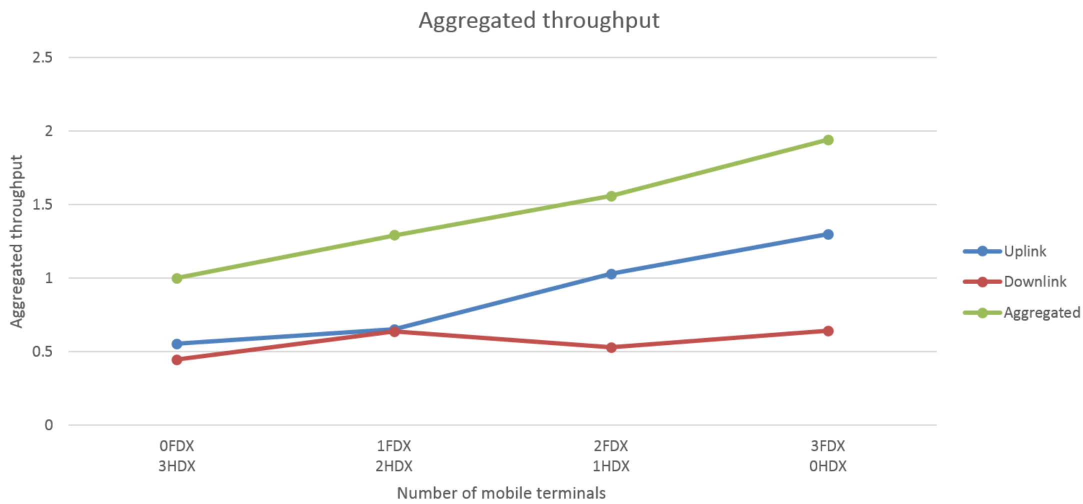


Figure 4.18: Aggregate throughput for 90% downlink load and 270% aggregate uplink load with 3 MTs.

its throughput by 1.44 times. Uplink throughput presents higher gains because the fairness control mechanism forces the saturated system to have 3 uplink slots followed by 3 downlink slots in the *0FDX - 3HDX* scenario. However, in the *3FDX - 0HDX* the fairness mechanism is not applied, making the continuous simultaneous communication between the AP and the MTs possible. Therefore, for *0FDX - 3HDX*, 6 slots are enough for the AP to receive 3 packets (one from each MT) and transmit 3 packets while in *3FDX - 0HDX*, 6 slots are enough for the AP to receive 6 to 9 packets (two to three from each MT) and transmit 2 to 3 packets.

The saturation aggregate throughput rises from 1.00 to 1.94, which means that for this scenario, having the nodes engage in FDX almost doubles the amount of packets that get exchanged as a whole.

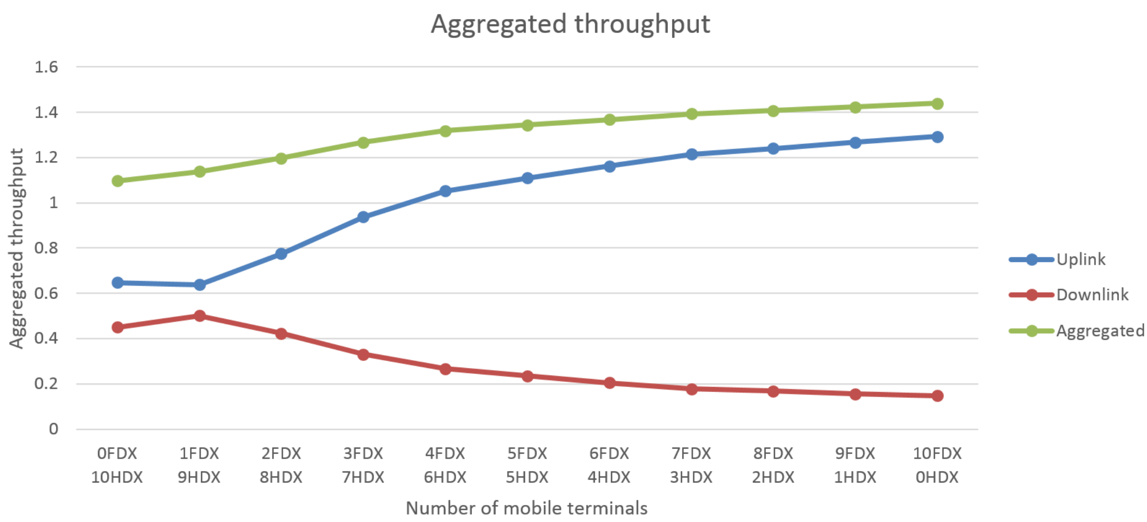


Figure 4.19: Aggregate throughput for 90% downlink load and 900% aggregate uplink load with 10 MTs.

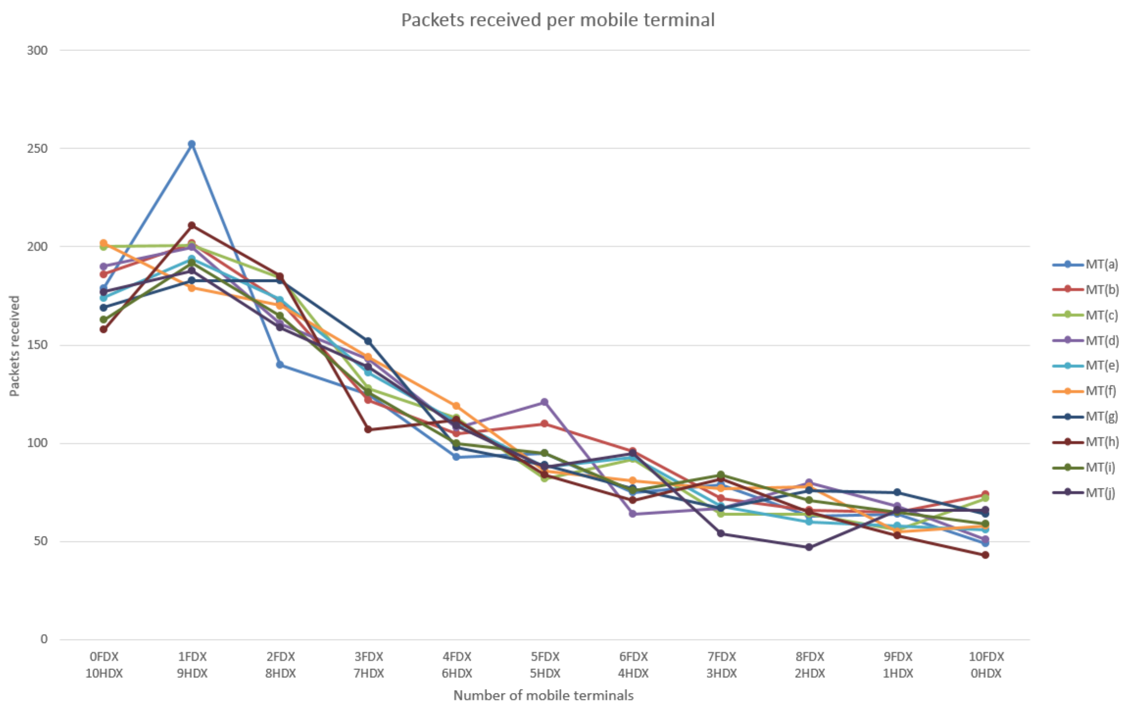


Figure 4.20: Packets received by each MT for 90% downlink load and 900% aggregate uplink load with 10 MTs.

Figure 4.19 shows that the uplink and downlink behaviours are inversely proportional in a completely saturated system, with 10 MTs. For *0FDX - 10HDX*, 14 slots are enough for the AP to receive 10 packets (one from each MT) and transmit 7 packets, while in *10FDX - 0HDX*, 14 slots allow the AP to receive 20 packets (two from each MT), but only transmit 2 to its destination. Since there are always 10 MTs accessing the channel at close quarters, the AP's destination usually requires 6 copies of the packet in order to be able

to resolve it properly. This wastes a lot of time in retransmissions, thus the AP will be able to deliver less packets in the same time interval. The aggregate throughput rises from 1.1 to 1.44, an improvement that is around 70% less than the one observed in the 3 MT scenario. It is well known that the saturated scenarios should be avoided. These results show that a saturated MPR-FDX system preserves its uplink capacity, however the downlink capacity collapses for a larger number of MTs.
Figure 4.20 depicts how the AP distributes its packets between all MTs in a saturated system. *1FDX - 9HDX* case might seem like an outlier, but instead is a scenario in which the only FDX MT in the system is constantly favoured. In this case, since the AP needs to open uplink slots, it prioritises packets for MT(a) in order to be able to transmit anything during that epoch. In order to provide a quantitative measure, the Jain's Fairness Index (JFI) [JCH84] metric was calculated. JFI $\mathcal{J}$ is given by

$$\mathcal{J}(x_1, \ldots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\left(\sum_{i=1}^{n} {x_i}^2\right)} \tag{4.3}$$

where x_i is the throughput for the ith connection of n users. $\mathcal{J}$ ranges from $\frac{1}{n}$ (least fair) to 1 (totally fair). As depicted in figure 4.21, $\mathcal{J}$ is roughly 1 for all scenarios, meaning the AP is able to distribute its packets in a fair manner.

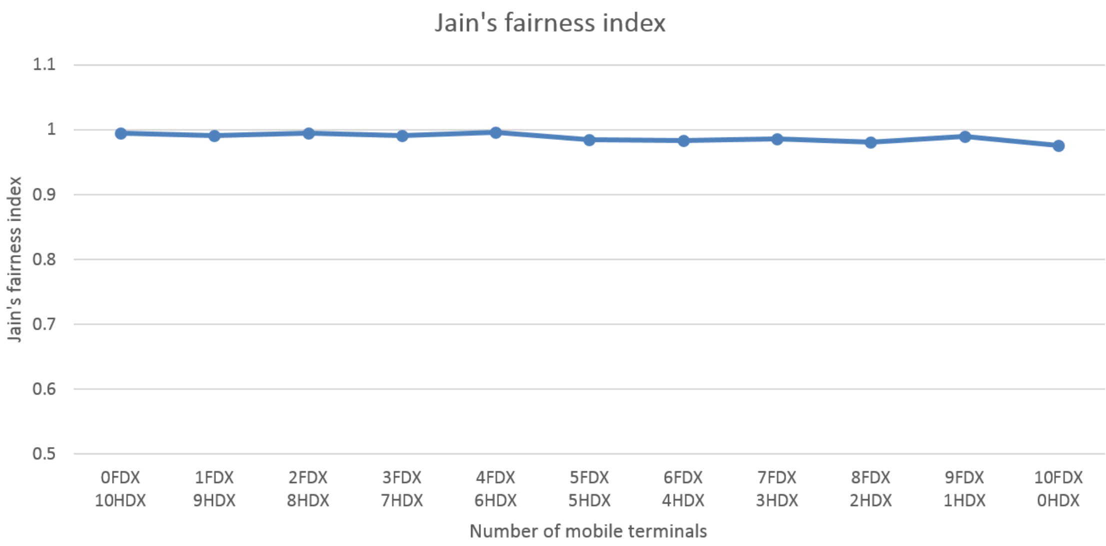


Figure 4.21: JFI for 90% downlink load and 900% aggregate uplink load with 10 MTs.

4.3.7 Simulation results overview

This section presented the simulation results for FM-MAC. It showed that having HDX MTs forces the entire system to reduce the number of packets delivered. Therefore, adding FDX MTs (or replacing HDX MTs by FDX ones) turns FM-MAC from a static with the same packet exchanges (k uplink slots followed by k downlink slots) into a dynamic system where uplink and downlink slots are temporally combined. This characteristic allows FM-MAC FDX's scenarios to outperform the HDX ones. One feature the protocol lacks is the ability to statistically estimate the uplink load of the MTs in the network. The current protocol design focuses too heavily on guaranteeing that at least 50% of the slots have uplink capability. This is important in high density scenarios, but greatly impacts HDX's delay and throughput if the MTs do not have a significant uplink load. It was also shown that SPR resolution by the MTs is adequate for low density scenarios, but MPR resolution is mandatory when a given MT has one or more MTs transmitting at close quarters. Another feature left for future work was a more precise management of ITI by the transmission of the exclusion SYNC. This mechanism was proposed, but it has not been tested yet.

A performance analysis with the potential of S-FDX is also not shown since the operating mode selector does not fully address this, due to the AP's inability to know if its destination is transmitting or not in the first slot of the epoch. A possible solution would be to use a combination between a statistic predictor and adding a one bit field to the MTs' DATA packets. These mechanisms can potentially improve the power efficiency and increase the FDX coverage radius, and will be handled in a post-dissertation research work.

5

Conclusions

5.1 Final considerations

This dissertation focused on analysing the impact of MPR in the presence of FDX communication.

Chapter 2 characterized the most significant FDX designs and their reported SIR values, as well as the techniques available to enable MPR. It showed that MPR has the potential to address the broader ITI generated by FDX communications.

Chapter 3 analyses the performance of MPR-IC and MPR-T based MPR receivers when FDX transmissions are used. It started by showing that higher values of SIR achieve lower BER when receiving packets and allow the transceiver to transmit at higher powers. It was also demonstrated that the coverage range of the MPR AP is not only connected to the SIR value of the transceiver, but also if the AP's destination is transmitting or not. MPR-T allows the node to reach higher distances, while MPR-IC manages to achieve the highest throughputs for small distances, but requires perfect power control, which can be hard to accomplish from a network's point of view.

Chapter 4 described FM-MAC, a novel MAC protocol that controls a system in which the AP supports both FDX and MPR and uses both technologies to maximize throughput. It was shown that HDX communications slows down the system as a whole, which directly impacts the system's throughput and delay. It was also demonstrated that in a high density scenario, MPR allows for a faster packet resolution than SPR. The current design's biggest flaws are that the AP is unable to identify if its destination is transmitting or not in the first slot of an UND epoch and that the AP forces at least 50% of the slots to have uplink capability (even when no MTs are transmitting).

5.2 Future work

In the scenario simulator, the FDX SIR residual noise is approximated by a null average Gaussian random variable with a variance equal to P_{SIR}. The Gaussian noise distribution is only valid for the sum of random independent variables and it is not guaranteed that the residual noise is completely independent from the transmitted signal. A more realistic scenario simulator could be implemented by using more precise noise models for the FDX SIR residual noise.

An interesting addition to FM-MAC would be having the nodes use power control in order to enable MPR-IC, so that a higher total throughput could be achieved, as described in chapter 3. The protocol's slot reservation issue can be addressed by having the AP statistically estimate the load of each MT in the system and have the amount of uplink slots be proportional to the aggregated uplink load. As for the AP inability to recognize if a given MT is going to transmit in the first slot of the epoch, a possible solution would be a combination between the statistic predictor mentioned above and adding a one bit field to the MTs' DATA packets. FM-MAC would also profit by having the AP using MIMO to enable multiple downlink flows simultaneously, as it would raise the system's downlink throughput.

Additional publications are envisioned based in this dissertation. We plan to prepare a conference paper covering the FM-MAC protocol, and an extended version, with a stochastic system level's performance model, for a journal. This work will be financed by project FCT MANY2COMWIN, under a research scholarship.

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A

Minimum transmission power tables

This appendix contains the tables extracted from the set of simulations that were described in section 3.3.1.2, regarding the minimum amount of power required for the AP or the MT to reach their destination at each given distance.

A.1 For half-duplex

Table A.1 shows the minimum amount of power required for the AP or the MT to reach its destination at each given distance with a PER below 1% for HDX.

Distance (metres)	P_t (dBm)
3	38
4	41
5	42
6	43
7	45
8	46
9	47
10	47
11	48
12	49
13	49
14	50
15	50
16	51
17	51
18	52
19	52
20	53
21	53
22	53
2	33
24	54
25	54
26	54
27	55
28	55
29	55
30	55
31	56
32	56
33	56
34	56
35	57
36	57
37	57
38	57
39	57
40	57
41	57
42	58
43	58
44	58
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81	63
82	63
83	63
84	63
85	63
86	63
87	63
88	63
89	64
90	64
91	64
92	64
93	64
94	64
95	64
96	64
97	64
98	64
99	64
100	64

Table A.1: HDX minimum transmission power

A.2 For a self-interference reduction of 80dB

Table A.2 shows the minimum amount of power required for the AP or the MT to reach its destination at each given distance with a PER below 1% for FDX with a SIR of 80dB.

Distance (metres)	P_t (dBm)
3	43
4	45
5	47
6	48
7	50
8	50
9	51
10	52
11	53
12	53
13	54
14	55
15	55
16	55
17	56
18	56
19	57
20	57
21	58
22	58
23	58
24	58
25	59
26	59
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81	67
82	68
83	68
84	68
85	68
86	68
87	68
88	68
89	68
90	68
91	68
92	68
93	68
94	69
95	69
96	69
97	69
98	69
99	69
100	69

Table A.2: FDX minimum transmission power for a SIR of 80dB

A.3 For a self-interference reduction of 90dB

Table A.2 shows the minimum amount of power required for the AP or the MT to reach its destination at each given distance with a PER below 1% for FDX with a SIR of 90dB.

Distance (metres)	P_t (dBm)
3	43
4	45
5	47
6	49
7	49
8	50
9	51
10	52
11	53
12	53
13	54
14	54
15	55
16	55
17	56
18	56
19	57
20	57
21	57
22	58
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77	67
78	67
79	67
80	68
81	68
82	68
83	68
84	68
85	68
86	68
87	68
88	68
89	68
90	68
91	68
92	68
93	69
94	69
95	69
96	69
97	69
98	69
99	69
100	69

Table A.3: FDX minimum transmission power for a SIR of 90dB

A.4 For a self-interference reduction of 100dB

Table A.2 shows the minimum amount of power required for the AP or the MT to reach its destination at each given distance with a PER below 1% for FDX with a SIR of 100dB.

Distance (metres)	P_t (dBm)
3	43
4	46
5	47
6	48
7	49
8	51
9	51
10	52
11	53
12	53
13	54
14	55
15	55
16	55
17	56
18	56
19	57
20	57
21	57
22	58
23	58
24	58
25	59
26	59
27	59
28	60
29	60
30	60
31	60
32	61
33	61
34	61
35	62
36	62
37	62
38	62
39	62
40	62
41	63
42	63
43	63
44	63
45	63
46	63
47	63
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49	64
50	64
51	64
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67	66
68	66
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72	66
73	67
74	67
75	67
76	67
77	67
78	67
79	67
80	68
81	68
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83	68
84	68
85	68
86	68
87	68
88	68
89	68
90	68
91	68
92	68
93	68
94	68
95	68
96	69
97	69
98	69
99	69
100	69

Table A.4: FDX minimum transmission power for a SIR of 100dB

A.5 For a self-interference reduction of 110dB

Table A.2 shows the minimum amount of power required for the AP or the MT to reach its destination at each given distance with a PER below 1% for FDX with a SIR of 110dB.

Distance (metres)	P_t (dBm)						
3	43	26	59	51	64	76	67
4	45	27	59	52	64	77	67
5	47	28	60	53	64	78	67
6	48	29	60	54	64	79	67
7	49	30	60	55	65	80	67
8	50	31	61	56	65	81	67
9	51	32	61	57	65	82	67
10	52	33	61	58	65	83	68
11	53	34	61	59	65	84	68
12	53	35	61	60	65	85	68
13	54	36	61	61	66	86	68
14	54	37	62	62	66	87	68
15	55	38	62	63	66	88	68
16	56	39	62	64	66	89	68
17	56	40	62	65	66	90	68
18	57	41	63	66	66	91	68
19	57	42	63	67	66	92	68
20	57	43	63	68	66	93	68
21	58	44	63	69	66	94	68
22	58	45	63	70	66	95	69
23	58	46	63	71	67	96	69
24	58	47	64	72	67	97	69
25	59	48	64	73	67	98	69
		49	64	74	67	99	69
		50	64	75	67	100	69

Table A.5: FDX minimum transmission power for a SIR of 110dB

B

Simulator's structure

B.1 Global architecture

The simulator's process is depicted in figure B.1. Firstly, the system's parameters are loaded into the simulator. For this, a MATLAB object called *systemObject* is created. This object contains all the information about the system, represented with the following attributes:

1. $time$: the time instant the simulator is at;
2. SYNC$time$, ACK$time$ and DATA$time$: the duration of each control and data packet;
3. $maxTime$: maximum simulation time (to be used as a stop condition for the simulator);
4. $normalizedPower$: the normalized power in dB. The power levels used by the terminals are calculated in relation to this value. The simulator uses the optimal power determined in section 3.3.1.1;
5. $Niter$: number of iterations used by the IB-DFE receiver;
6. fc: centre frequency (in GHz);
7. $distanceMatrix$, $xiMatrixHDX$ and $xiMatrixFDX$: distance and channel coefficient matrices. This concept will be described with more detail in section B.2;
8. $FDXMatrix$ and $HDXMatrix$: minimum transmission power tables (as depicted in appendix A);

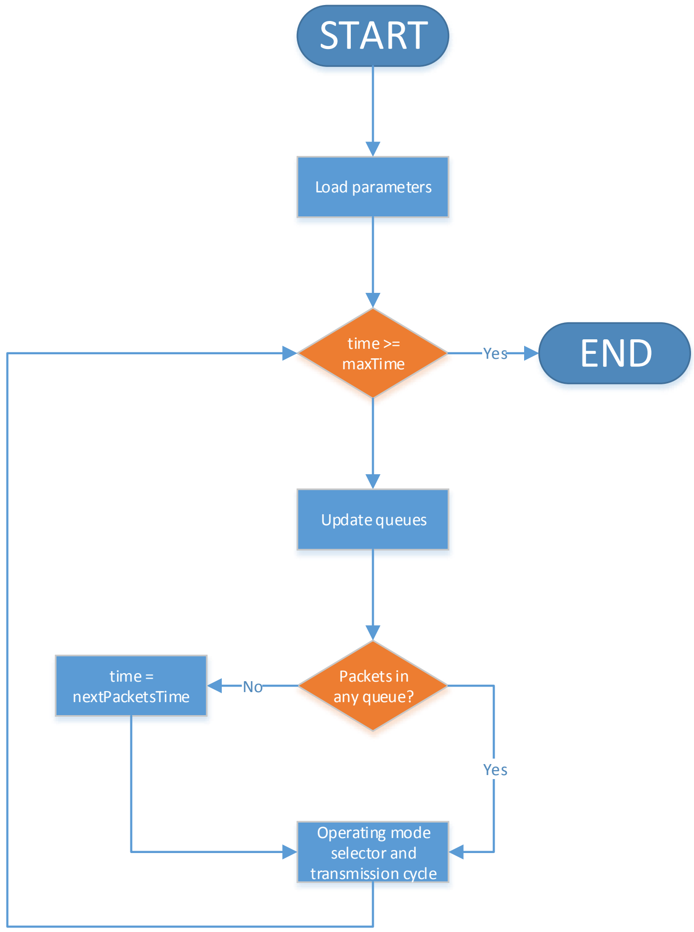

Figure B.1: Flowchart representing the simulator's process.

9. $creditsDownlink$: the downlink credits available at the time;
10. $maxCredits$: variable that prevents the AP from having too many credits and makes sure that there are not too many FDX packets being favoured. Calculated using equation 4.1;
11. $terminal$: an array of objects which contains the proprieties of all the terminals. The AP is always the last terminal in this array.

Each terminal is modelled by a set of technical and statistical attributes. The technical attributes characterize and define the terminal's behaviour in the system. The statistical attributes allow the quantification of the terminal's performance in the system, which are used for the determination of statistical measures *a posteriori*. The technical attributes are:

- $coordinates$: geographical position of the terminal in relation to the AP;
- $directionalGain$: the gain of the antenna the terminal is using;
- SIR: amount of SI the terminal is able to reduce expressed in dB;

- $timeGenerationPacket$: array that contains the instants in which the packets are generated;
- $destination$: array that contains the destination for each packet generated. In the current version of the simulator, all MTs' destinations are set to the AP, but in future work, this can be modified to simulate inter-terminal packet exchanges through the AP;
- $packetsInQueue$: number of packets still in queue;
- $idle$: boolean variable to indicate if the terminal wants to transmit. True if $packetsInQueue > 0$.

The statistical attributes are:

- $successfulTransmissions$: number of successful transmissions. Coincides with the number of packets delivered to the terminal's destination;
- $unsuccessfulTransmissions$: number of unsuccessful transmissions;
- $packetsDropped$: number of packets dropped;
- $timePacketEnteredQueue$: array that contains the instants in which the packets are added to the queue;
- $timeTransmissionStart$: array that contains the instants in which the packets start to be transmitted;
- $timeTransmissionEnd$: array that contains the instants in which the terminal ceased transmission for each packet;
- $transmissionsNeeded$: array that contains the number of transmissions required for each packet to be received;
- $resolutionMode$: array that contains the type of resolution used for the reception of the packet (SPR or MPR);
- $timePacketDropped$: array that contains all the instants in which there was a packet drop;
- $TXpower$: array that contains the power levels used for each transmission.

After all these attributes are set, the simulator enters into a loop. At the start of each cycle, the stop condition $time > maxTime$ is checked. If false, the simulator uses the current $time$ to update the queues of all terminals and checks if there are any terminals with packets pending. If there aren't, the simulator jumps to the next event ($time =$ **nextPacketsTime**). Otherwise, the last routine, called **Operating mode selector and transmission cycle** is run. Its main objectives are:

1. Select the operating mode that respects the protocol;
2. Simulate the reception by all terminals;
3. Update the $time$ variable.

The operating mode is selected using algorithm 2 described in section 4.2.8.
The receptions are simulated by running several iterations of the IB-DFE receiver presented in chapter 3 for each time slot. To simulate receptions at the AP, only one iteration needs to be ran for each time slot, whereas to simulate receptions at the MTs, two iterations of the IB-DFE receiver are ran, in order to determine the PER for SPR and MPR resolution. The current design always uses the type of resolution that provides the lowest PER. When FDX communications take place, three iterations of the IB-DFE receiver are ran for each time slot. To determine which packets get delivered, each reception's PER is compared to a uniform random number in the interval [0,1]. If the PER is inferior to this number, the packet is assumed to have been delivered to its destination. With each transmission, the attributes in the $terminal$ object are updated.
Lastly, the $time$ variable is updated by adding the duration of the control and data packets used in the transmission cycle.

B.2 Distance and channel coefficient matrices

After all parameters are loaded, the simulator starts by calculating the distance from all terminals to all terminals (AP included). This information is stored in the distance matrix and allows the determination of the FDX channel coefficient and the HDX channel coefficient for each distance. The channel coefficient matrices are denoted by $xiHDX$ and $xiFDX$ and represent the difference to the normalized power (52dBm for the considered case). As covered in section 4.2.6, a terminal that wants to transmit uses $xiHDX$ if its destination is not transmitting and uses $xiFDX$ if its destination is transmitting. The channel coefficient xi ranges from 0dB (no attenuation) to $-Inf$dB (no transmission). It allows the measurement of the power that reaches the AP and each MT in all transmissions and can be calculated using

$$xi = \text{linear2db}\left(\sqrt{\text{db2linear}\left(offset(d) + G_0 + P_L(d)\right)}\right), \tag{B.1}$$

where linear2db(x) denotes the conversion from linear to dB, db2linear(x) denotes the conversion from dB to linear, $offset(d)$ denotes difference between the power level used by each terminal in order to reach the AP (according to tables A.1 and A.2) and the normalized power level of the simulator, G_0 denotes the antenna gain and $P_L(d)$ denotes the path loss model defined by ITU [Itu]. The xis between the AP and all MT are roughly the same and symmetrical (xi for MT $\rightarrow$ AP = xi for AP $\rightarrow$ MT). However, the xis between the MTs may differ and are not necessarily symmetrical. This happens because the system is dimensioned so that all MTs reach the AP with the same average power. Figure

B.2 depicts an example with 2 MTs.

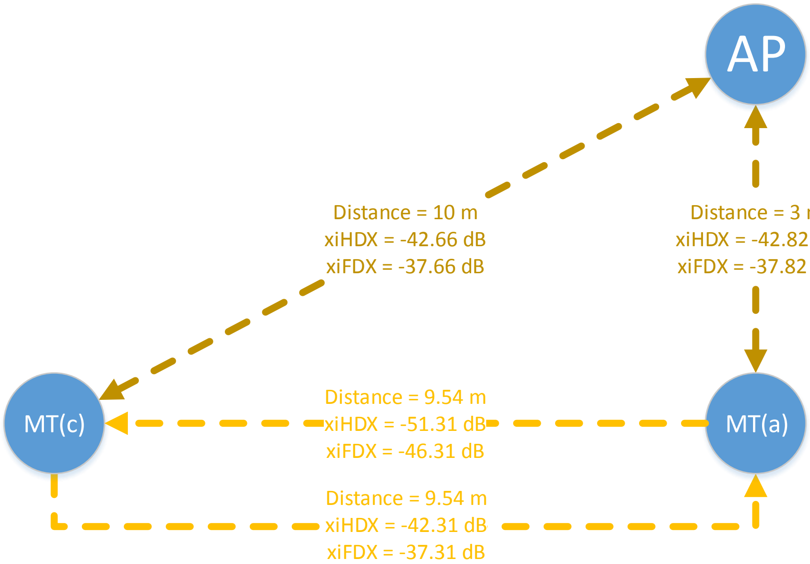

Figure B.2: Determined parameters for 2 MTs.

B.3 Output

At the end of each simulation, the simulator produces two MATLAB cell arrays: *statsTable* and *logTable*. *statsTable* contains a statistical analysis of the simulation and *logTable* contains the characterization of what happened in each time slot, organized in a set of operating mode's epochs (time interval between the two SYNCs). An example of *statsTable* and *logTable* is shown in figures B.3 and B.4 respectively. The tables depicted are illustrations of the simulations used for the throughput analysis of the dissertation with 90% downlink load and 270% aggregate uplink load with 3 MTs.
Figure B.3 depicts the *statsTable* cell. The queueing delay is defined by the time a packet waits in queue and can be calculated by subtracting the time a packet starts to be transmitted to the time the packet enters the queue. The service time is defined by the time it takes for a packet to be delivered and can be calculated by subtracting the time the terminal ceases transmission for a given packet to the time a packet starts to be transmitted.
Figure B.4 depicts the *logTable* cell. Each line represents an operating mode's epoch (time interval between the two SYNCs). Its columns are:

- Epoch Start: time the SYNC broadcast finishes;
- Epoch End: time the SYNC broadcast begins;
- Operating Mode: operating mode used in the epoch;
- Terminals Transmitting: terminals transmitting in the epoch. The AP includes its destinations between brackets;

statsTable <19x5 cell>

	1	2	3	4	5
1	[]	'User 1 (FDX)'	'User 2 (FDX)'	'User 3 (HDX)'	'AP'
2	'Min Nro. TX'	2	2	2	1
3	'Max Nro. TX'	3	3	3	2
4	'Average Nro. TX'	2.0357	2.0379	2.0357	1.6383
5	'Min Queuing Delay'	311.9792	332.6171	315.2048	174.6279
6	'Max Queuing Delay'	2.8344e+03	2.7732e+03	2.8083e+03	1.8292e+03
7	'Average Queuing Delay'	1.5826e+03	1.5734e+03	1.5893e+03	994.9204
8	'Min Service Time'	2.1000	2.1000	2.1000	1
9	'Max Service Time'	3.2000	3.2000	3.2000	2.1500
10	'Average Service Time'	2.1393	2.1417	2.1393	1.7034
11	'Successfull Transmissions'	1373	1373	1373	2112
12	'Unsuccessfull Transmissions'	1422	1425	1422	1348
13	'Total Transmissions'	2795	2798	2795	3460
14	'Packets Received'	687	717	708	4119
15	'Packets Dropped'	0	0	0	0
16	'Packet Delivery Ratio'	0.4912	0.4907	0.4912	0.6104
17	'Throughput'	0.3433	0.3433	0.3433	0.5280
18	'Total Energy'	110.9687	110.9851	124.9494	120.5213
19	'EPUP'	48.2152	48.2317	62.1960	54.0274

Figure B.3: *statsTable* for 2 FDX MTs and 1 HDX MT for 90% downlink load and 270% aggregate uplink load.

- DATA Slots Used: number of slots contained in the epoch;
- TX Summary: cell that contains the successful transmissions;
- Xi: cell that contains the xis, the SIR value and the offset used for each transmission by the AP and the MTs. A detailed view of this cell is depicted in figure B.5;
- PER: cell that contains the PER associated to each transmission.

Figure B.5 depicts an example of a xi cell. Each line represents the parameters set for each transmission. Its columns are:

- xi: the channel coefficient matrices used for the calculation of the reception at each terminal;
- SIR: the noise the terminal is able to reduce. A SIR of InfdB means the given terminal did not transmit in that time slot (HDX);
- Offset: difference between the power level used by each terminal in order to reach the AP (according to tables A.1 and A.2) and the normalized power level of the

logTable <2602x9 cell>

	1	2	3	4	5	6	7	8
1	'Epoch Start'	'Epoch End'	'Operating Mode'	'Terminals Transmitting'	'DATA Slots Used'	'TX Summary'	'Xi'	'PER'
2	1.2500	3.3000	'UO'	'1,3'	2	<3x2 cell>	<3x3 cell>	<3x2 cell>
3	3.4000	5.5500	'UND'	'1,2,3,AP(2)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
4	5.6500	6.7000	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
5	6.8000	9.9000	'UO'	'1,2,3'	3	<4x3 cell>	<4x3 cell>	<4x3 cell>
6	10.0000	11.0500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
7	11.1500	13.3000	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
8	13.4000	14.4500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
9	14.5500	16.7000	'UND'	'1,2,3,AP(2)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
10	16.8000	17.8500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
11	17.9500	20.1000	'UND'	'1,2,3,AP(2)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
12	20.2000	22.3500	'UND'	'1,2,3,AP(2)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
13	22.4500	24.6000	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
14	24.7000	25.7500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
15	25.8500	29.1000	'UND'	'1,2,3,AP(2)'	3	<4x4 cell>	<4x7 cell>	<4x4 cell>
16	29.2000	30.2500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
17	30.3500	32.5000	'UND'	'1,2,3,AP(2)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
18	32.6000	33.6500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
19	33.7500	35.9000	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
20	36.0000	37.0500	'DO'	'AP(3)'	1	<2x1 cell>	<2x3 cell>	<2x1 cell>
21	37.1500	39.3000	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
22	39.4000	41.5500	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
23	41.6500	43.8000	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>
24	43.9000	46.0500	'UND'	'1,2,3,AP(1)'	2	<3x4 cell>	<3x7 cell>	<3x4 cell>

Figure B.4: *logTable* for 2 FDX MTs and 1 HDX MT for 90% downlink load and 270% aggregate uplink load.

logTable{77, 7} <4x8 cell>

	1	2	3	4	5	6	7
1	'xi Terminal'	'SIR Terminal'	'Offset Terminal'	'xi AP'	'SIR AP'	'Offset AP'	'Resolution Terminal'
2	<1x3 cell>	'80'	'-5'	<1x3 cell>	'80'	'-5'	'SPR'
3	<2x3 cell>	'80'	'-5'	<2x3 cell>	'80'	'-5'	'MPR'
4	<1x2 cell>	'Inf'	'NA'	<3x3 cell>	'80'	'-10'	'SPR'

Figure B.5: Example of a xi cell.

simulator. Not Applicable (NA) means the given terminal did not transmit in that time slot;

- Resolution Terminal: Type of resolution used at the MT. The type of resolution used is always the one that produces the minimum PER.